PERFORMANCE MATCHING AND PREDICTING OF A GEOTHERMAL RESERVOIR

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN CIVIL ENGINEERING

AUGUST 1976

By

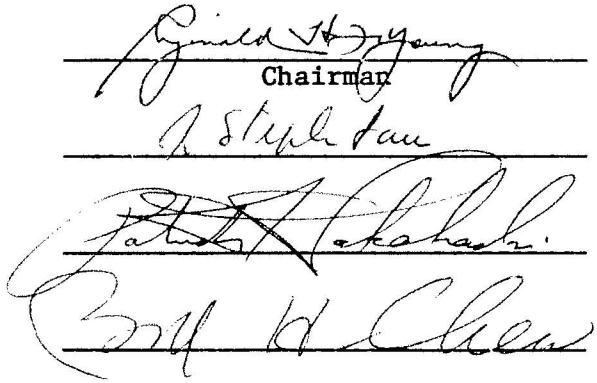
Arthur Satoshi Seki

Thesis Committee:

Reginald H.F. Young, Chairman
Bill H. Chen
L. Stephen Lau
Patrick K. Takahashi

We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

THESIS COMMITTEE



Chairman

ABSTRACT

The initial conditions (physical and chemical state) of a geothermal reservoir and its fluids are important information needed in geothermal reservoir engineering for determining the future productivity of the reservoir. An optimization scheme was employed to minimize the least squares function and determine the optimum initial conditions. Using the mass, energy, and volumetric balance equations, the initial parameters were obtained by matching the production data plot of average reservoir pressure versus cumulative mass produced for a compressed liquid, saturated liquid-steam, and superheated steam reservoir. Once a good curve match was attained, the performance projection of the geothermal reservoir was made at different production rates. A successful curve match was found to be highly dependent on the constraints chosen in the optimization scheme. Mass influx, as well as porosity also proved to be an influencing factor in the determination of the initial conditions.

TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

Figure | Page

I. INTRODUCTION

It is becoming quite evident that the United States' stocks of primary energy resources, oil and gas, are diminishing. By the turn of the century these natural resources may be completely depleted. The oil crisis a few years ago was evidence of the United States' dependency on foreign resources. It is therefore very important that the United States become as self-sufficient as possible in energy matters.

Research has already been directed to evaluate solar, wind, and ocean thermal differential as potential energy sources. Nuclear and geothermal plants are presently in operation. Of all energy sources currently available, geothermal energy requires the least capital cost per kilowatt [1].

One of the primary uses of the geothermal resources is for the generation of electricity, although only 1% of the total available energy can be converted to electrical energy from a hot-water reservoir using the present proven technology, while the equivalent figure for a vapor-dominated reservoir is 2-5% [2]. The other uses of geothermal heat have been for the heating and air-conditioning of buildings, the heating of hot-houses and soil for agricultural purposes, recreational activities, and product processing. Geothermal energy also has potential use in refrigeration and freeze drying. Some geothermal fluids contain potentially valuable chemical by-products such as potassium, lithium, calcium, and other metals.

In the United States, only one geothermal reservoir plant has been in operation at Geysers, California, since 1960. There has been a

geothermal plant in operation since the early 1900's at Lardarello, Italy.

A question arises as to why there have been few advancements in geothermal reservoir engineering.

The reasons are [1]:

1. The exploitation of geothermal energy is just beginning. There was a lapse of about one century in petroleum reservoir engineering.
2. There has been minimal interchange of ideas and methods among practitioners in the field. Literature in this field is relatively sparse because the industry treats well testing methods, data, and methods of analysis as proprietary.
3. Geothermal reservoir engineering is complicated by the existence of high downhole temperatures.

The United Nations has played an important role in unifying geothermal technology. This was demonstrated in May of 1975 when representatives from fifty-nine nations attended a ten-day conference on geothermal resources. Six other distinct groups have contributed to the further development of geothermal reservoir engineering: Energy Research and Development Administration, Bureau of Reclamation, United States Geological Survey, New Zealand government, Stanford University, and University of Hawaii.

Congress adopted the Geothermal Steam Act in December of 1970, which established the development of the United States' geothermal resource as a national goal. With the new increased interest in geo-

thermal energy, emphasis has been placed on the development of modern geological and reservoir principles to provide estimates of the reserves and the future productivity of geothermal fields [3].

Robert L. Whiting and Henry J. Ramey Jr. [4] developed a mathematical computer model to match and predict the performance of a geothermal reservoir at Wairakei, New Zealand. To date, this has been the only work of this type published.

The objective of this study is to develop a mathematical model to match past performance of a geothermal reservoir, whether its physical state is as compressed liquid, saturated liquid-steam, or superheated steam, and to predict future productivity. The computer model employs essentially the same material-energy balance equations used by Whiting and Ramey [4]. Special attention has been paid to sensitivity analysis on various parameters wherever applicable, and on the optimization technique used for matching reservoir performance.

II. BACKGROUND

II.1. Geothermal Reservoirs

Geothermal reservoirs can be categorized into two general types: hot-water fields and vapor-dominated fields. The hot-water fields represent compressed liquid and saturated liquid-steam reservoirs; vapor-dominated fields are systems with a significant dry steam region.

II.1.1. Hot-Water Field Characteristics

The temperature of the fluid in the reservoir may range up to 600°F. Hot-water dominated systems are more prevalent than vapor-dominated ones. The former type is the most common type of economically exploitable geothermal field (Table 1).

The geology of hot-water fields is similar to that of cold groundwater systems. Arguments have been advanced that systems suitable for exploitation may be confined (artesian) or open (without a caprock, a layer of rock with low permeability overlying the aquifer). Hot-water systems are usually found in permeable sedimentary or volcanic rocks and rocks such as granite, with open channels along faults or fractures [5].

Hot-water systems have a high potential for self-sealing because of deposition of minerals in outlet channels. Silicates, calcites, and sodium dioxide are important constituents contributing to the self-sealing of high temperature systems, because they are relatively abundant and their solubility increases greatly with increasing temperature. Therefore, where large temperature differences exist, self-sealing may

Table 1. Characteristics and Power-Generating Capacity of Selected Geothermal Fields

Country	Field	Reservoir Fluid	Temperature, °F	Electrical Capacity, MW
New Zealand	Wairakei	water	518	192
	Kawerau	water	-	10
Mexico	Cerro Prieto	water	572	75
Japan	Otake	water	392	13
	Matsukawa	mostly steam	446	20
U.S.	Geysers	steam	473	502
Italy	Larderello	steam	473	365
	Monte Amiata	steam	-	25

be expected. The self-sealed reservoir eventually becomes a closed reservoir, which is depletable.

Under ideal thermodynamic conditions hot water will flash up a well drilled into a geothermal reservoir. The resulting fluid is a mixture of water and steam under saturated liquid-steam conditions, with water usually predominating. The proportions of water and steam vary with each well in a single field in accordance with the enthalpy of the fluid and the wellhead pressure. Once flow has been initiated, a production well in this type of field will flow continuously [6].

II.1.2. Vapor-Dominated Field Characteristics

Dry steam fields are those that yield dry or superheated steam (Table 1). Geologically, hot-water and dry steam fields are generally similar, as emphasized by the fact that in some cases wells have produced hot water for a period and dry steam later [6].

It has been known that the near-surface rocks of Larderello and Geysers are relatively tight and evidently do not permit large quantities of meteoric water to penetrate deep into their systems [5]. Tight reservoir rock, which has low porosity and permeability, develops a superheated region more quickly during its production life than rock which has high permeability [7].

In general, when surface springs are low in chloride and subsurface thermal waters are similarly low (<20 ppm, parts per million), a vapor-dominated system is indicated. The chloride content of steam is normally less than 1 ppm, but near-surface waters involved in condensation of the steam commonly contain a few ppm of chloride because, with little or

no discharge, chloride can be selectively concentrated [5].

II.1.3. Source and Transfer of Heat

Non-geopressured reservoirs obtain heat from underground magmatic intrusions. The heat source may reach temperatures as high as 2400°F. In an active volcano, a magmatic intrusion reaches the surface through a large fault system. Magmatic intrusions that have occurred within the last half million years or so may satisfactorily account for the heat source, depending on the closed system characteristics of the reservoir [6].

Conduction is the primary means by which the heat is conveyed through the rock strata. In addition, heat can be transferred by convection, especially in a reservoir where fluid passes through rock of sufficient permeability [7]. Generally, when the density of the saturating fluid phase in a porous medium is not uniform, some movements caused by the effects of gravity forces may occur and tend to reduce the overall discrepancies in the density field [8]. Cold water travels from the upper to the lower part of the aquifer. The most common parameter that influences density of a fluid is temperature (usually density decreases when temperature increases), which tends to stablilize at or near the boiling point corresponding to the hydrostatic pressure of the system. Temperature inversions, which are not uncommon, cause secondary disturbances in the convection network [6].

If the water recharge rate is insufficient to balance the draw-off of the steam, and "evaporative space" will form in the vicinity of the production zone. Eventually, a comprehensive steam zone may form above

the water reservoir. Evidence shows that the steam-water interface tends to fall, if production is high, until a point of equilibrium is reached. This change is dependent on the recharge rate [6].

The fluid reaching the surface has approximately the same energy as that entering the well formation. Dry steam reaches the surface with little change, but water entering at high temperatures or liquid-steam mixtures boil on the way up the casing, losing temperature and pressure in accordance with saturated conditions [9].

II.2. Computer Models of Geothermal Reservoirs

Several computer models for geothermal reservoirs have been developed. These may be divided into two general types: distributed-parameter models and lumped-parameter models. A model in which the properties of the rock and/or the fluid (e.g. saturation, viscosity, pressure, etc.) are allowed to vary in space is called a distributed-parameter model. Numerical analysis is usually the method employed to solve the problem.

The lumped-parameter model offers one of the simplest means of describing the behavior of a geothermal system during exploitation and is of main interest to this study. In the lumped parameter model, the entire system is considered a perfect mixing cell for both mass and energy, so the spatial variations in concentration can be reduced to a single point in space. Instead of considering the internal distribution of mass and energy, attention is restricted to the total amounts generated within the system as well as those crossing the boundaries. Since time is the only independent variable, the system can be characterized

mathematically by a set of ordinary differential equations or an equivalent set of algebraic expressions representing total mass and energy [10]. A few people have done research with this model. Their work will be discussed briefly.

II.2.1. Brigham-Morrow Model

The lumped-parameter approach was adapted to vapor-dominated system by considering three different distributions of vapor and liquid. In each case the system is assumed to be completely closed (i.e. the boundaries are impermeable and adiabatic) and energy is derived only from the rock mass itself.

The first model concerns a single-phase system completely saturated with vapor. An isothermal system was assumed in this model. The second model has the vapor phase separated from an underlying layer of liquid by a horizontal interface at which boiling occurs. The vapor phase is assumed to be isothermal, while the liquid phase changes its volume continuously and the corresponding lumped system is therefore defined as the pore space filled with liquid at the beginning of each pressure drop. The final model in question considers a vapor phase overlying a layer of liquid except that boiling occurs throughout the entire thickness of this layer and its depth remains fixed with time. The resulting energy equation is essentially similar to that of Whiting and Ramey [4] with the exception that only steam is allowed to leave.

Applications of these models to various hypothetical reservoirs has shown that in estimating available reserves by extrapolation of early P/Z (pressure/compressibility factor) behavior, the results will tend to

be optimistic when porosity is low, but pessimistic when porosity is high. The presence of even a small amount of liquid in the lower part of a geothermal system is extremely important since it can account for a large fraction of the total fluids mass and significantly affect the P/Z analysis. Finally Brigham and Morrow concluded that the steam region will always remain isothermal whether or not there is boiling water below the steam. Thus pressure, temperature, and enthalpy measurements will not be completely diagnostic for determining the original state of the reservoir as steam gradually becomes superheated as pressure declines [11].

II.2.2. Martin Model

This lumped-parameter model is based upon the assumption that the liquid and gas phases are uniformly distributed throughout the system. The system is assumed to be completely closed and each phase is produced at a rate related to its relative permeability.

Martin [12] stated that the depletion of a reservoir, if it is initially in the compressed liquid region, will be isothermal until saturation conditions are met. Steam production increases in the reservoir along the vapor pressure curve to the point where all the liquid has vaporized. The reservoir will then produce superheated steam essentially under isothermal conditions.

II.2.3. Whiting-Ramey Model

This is the first and best known lumped-parameter model of a producing geothermal reservoir The system has a bulk volume containing

vapor, water, and rock. Water may flow in from an adjacent aquifer or leak out of the system via steam vents, springs, wild wells, etc. The water influx is represented by a linear combination of terms each of which is the product of a theoretical time-dependent response function characterizing a certain aquifer flow geometry (hemispherical, linear, or radial) and pressure. These calculations further assume that the liquid inflow is isothermal with constant enthalpy. The energy balance calculation is based on the assumption that the system is in complete thermodynamic equilibrium. Additional assumptions made are that the heat loss is negligible, while the enthalpy of the produced and lost fluid is the same.

The compressed liquid version of this model was applied to the Wairakei geothermal system in New Zealand. The model was successfully used to match and predict the performance of the reservoir [4].

Of the three models discussed above only Whiting and Ramey's model provides for estimates of reserves and future productivity. The Hawaii Geothermal Project (HGP) model will be somewhat similar to Whiting and Ramey's model.

III. THEORETICAL CONSIDERATIONS

III.1. Basic Equations

The following basic equations have the capacity for describing any geothermal reservoir containing liquid and/or steam, including production and recharge in any physically possible fashion, whether it be compressed liquid, superheated steam, or any liquid-steam mixture. They are the material balance, energy balance, volumetric balance, and enthalpy equations.

Material Balance:

$$W_c = W_i - W_p - W_L + W_e \tag{1}$$

where W_c = current mass in reservoir, lb

W_i = initial mass in reservoir at start of production, lb

W_p = cumulative mass produced, lb

W_L = cumulative mass lost via springs, wild wells,etc., lb

W_e = cumulative liquid mass influx, lb

Energy Balance:

$$W_c H_c = V(1-\phi)\rho_r C_r (T_i - T_c) + W_i H_i - W_p H_p - W_L H_L + W_e H_e + Q_s \tag{2}$$

where H_c = average enthalpy of total fluids in reservoir, Btu/lb

H_i = average enthalpy of initial fluids in reservoir, Btu/lb

H_p = average enthalpy of produced fluids, Btu/lb

H_L = average enthalpy of lost fluids, Btu/lb

H_e = average enthalpy of liquid water influx, Btu/lb

V = reservoir bulk volume, ft^3

ϕ = formation porosity

ρ_r = formation density, lb/ft^3

C_r = specific heat of formation, Btu/lb-°F

T_c = current reservoir temperature, °R

T_i = initial reservoir temperature, °R

Q_s = cumulative net heat conducted into reservoir, Btu

Volumetric Balance:

$$V\phi = W_c((1-X_c)V_f + X_cV_g) \tag{3}$$

where X_c = current steam quality in reservoir

V_f = specific volume of saturated liquid, ft^3/lb

V_g = specific volume of saturated vapor, ft^3/lb

Enthalpy Equation:

$$H = (1-X)H_f + XH_g \tag{4}$$

where H = fluid enthalpy of steam quality X, Btu/lb

H_f = enthalpy of saturated liquid, Btu/lb

H_g = enthalpy of saturated vapor, Btu/lb

Equations (1), (2), (3), and (4) are the basic equations employed by Whiting and Ramey [4].

III.2. Physical States of Water

In the use of Gibbs' phase rule, in order to specify the thermodynamic state of a single phase of water, two independent thermodynamic

properties (i.e. temperature and pressure) must be specified. However, if two phases are present (e.g. saturated liquid-steam), specification of only one intensive property defines the system.

$$d_f = C - P + 2 \tag{5}$$

where d_f = degrees of freedom

C = number of components

P = number of phases

It has been shown through thermodynamic analysis that a geothermal system initially yielding a single-phase (either compressed liquid or superheated steam) will tend to deplete isothermally. However, once two phases form, a system should follow a variation of the vapor pressure curve appropriate for the fluids in the pore space [13].

III.3. Thermodynamics

In the following section is discussed five possible initial conditions (Figure 1) the geothermal reservoir may have and their probable paths during mass production. It is assumed that water influx is negligible.

The first case to be considered is state "A", which lies entirely in the vapor region. Recall from Gibbs' phase rule that two intensive properties completely determine the thermodynamic state of the system. A pressure-enthalpy plot (Figure 2) for pure water in the superheated steam region shows the path of isothermal production of a geothermal steam reservoir initially at point "A" [4]. Although the actual path for production of such a reservoir would not truly be isothermal, the temperature decline would be too small to detect using normal field instru-

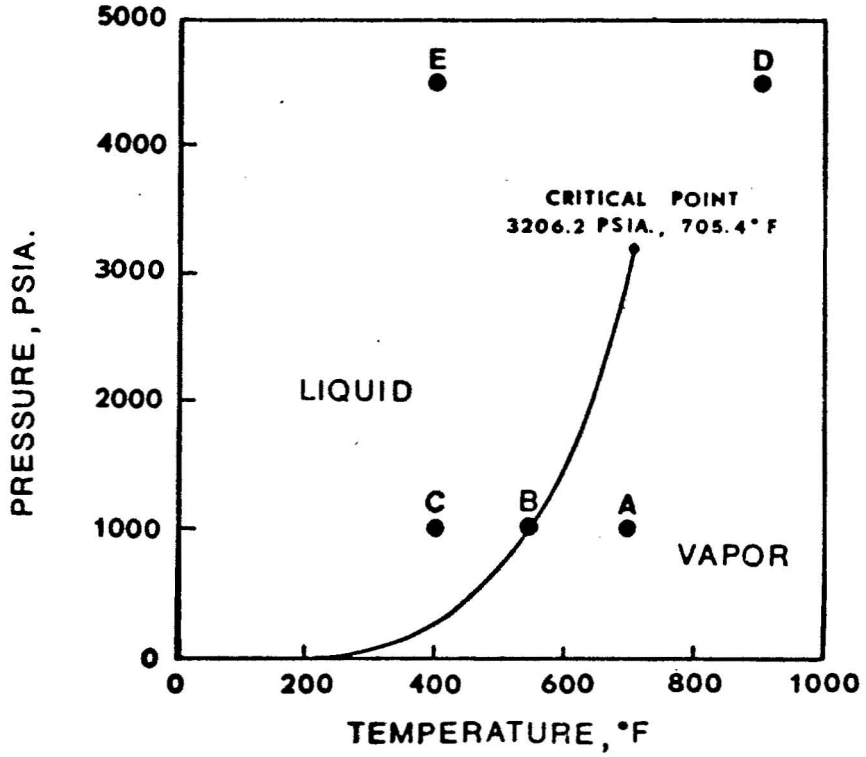


Figure 1. Pressure-Temperature Diagram for Water [4]

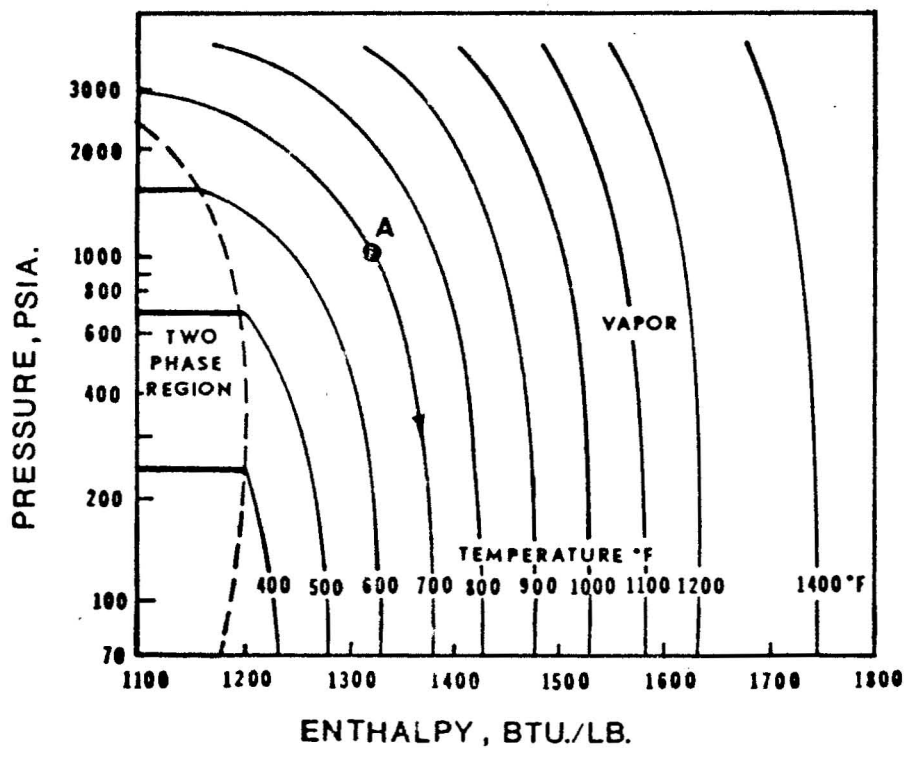


Figure 2. Pressure-Enthalpy Diagram for Superheated Steam [4]

ments. The enthalpy of the steam in the reservoir increases significantly with a pressure drop as reported at Larderello, Italy [14]. If the reservoir follows an isoenthalptic path with both pressure and temperature declining, then the thermal energy is obtained from the large quantity of sensible heat in the rock matrix [4].

Point "B" in Figure 1 lies on the vapor pressure curve. According to Gibbs' phase rule, one intensive property determines this type of system. Although the thermodynamic condition is specified as solid, liquid, and vapor in equilibrium, the relative amounts cannot be determined unless other thermodynamic properties are known (e.g. enthalpy, steam quality,etc.). Point "B" in Figure 3, a pressure-enthalpy diagram for pure water, best illustrates this point.

The mass and energy of the produced fluid and the thermodynamic path of the producing fluid must be specified. If saturated hot water was produced isothermally, there would be no reservoir pressure decline until all the fluid in the reservoir had vaporized. If the reservoir follows an isoenthalptic path, both pressure and temperature would tend to decrease. Transfer of heat from the rock to the fluids in the pore space would occur [4]. One important fact remains clear as long both liquid and vapor exists in the reservoir: the maximum enthalpy of steam would be 1204.5 Btu/lb (Figures 2 and 3). Furthermore, the reservoir steam enthalpy should decline slightly as reservoir steam pressure decreases below 700 psia. Therefore, enthalpy of the produced geothermal fluid may well provide important information regarding reservoir conditions.

The compressed liquid state is represented by point "C" in Figures

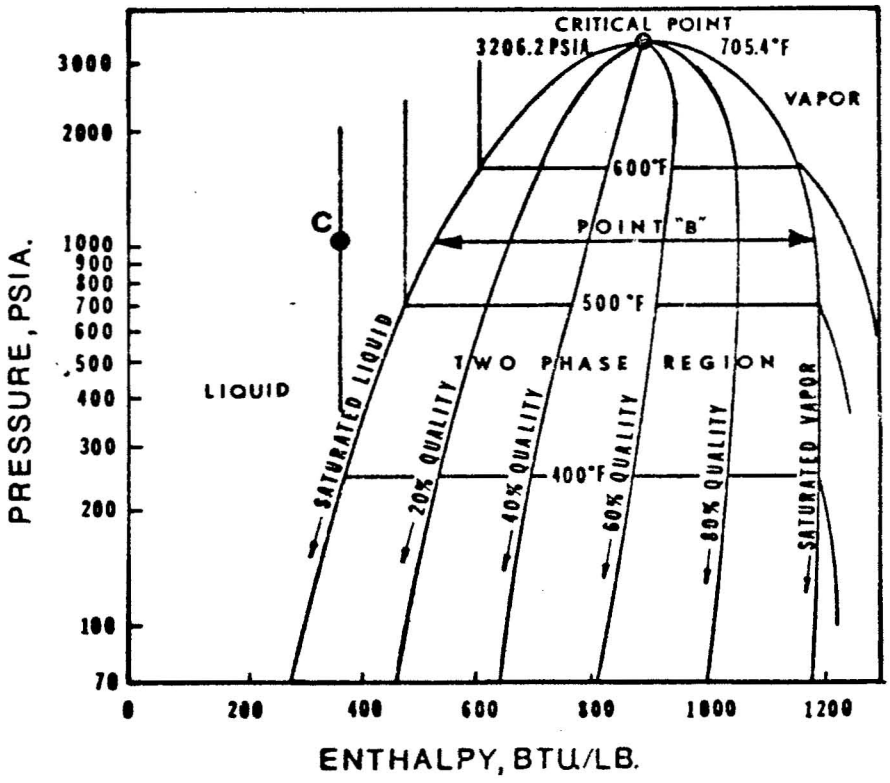


Figure 3. Pressure-Enthalpy Diagram for Water [4]

1 and 3. Similarly as for point "A", both initial pressure and initial temperature are needed to determine the initial condition. The difference lies in that point "C" will eventually reach some point "B" on the vapor pressure curve. The actual path of the compressed liquid reservoir is essentially isothermal and isoenthalptic [4].

Points "D" and "E" represent pressures higher than critical. A geothermal reservoir indicated by point "D" would eventually become similar to a reservoir initially at condition "A". An initial reservoir condition like point "E" would soon become similar to points "C" and "B" upon steam production and resultant pressure decline.

III.4. Pressure Buildup Test

Of all the well test analyses, the pressure buildup test is the most important because it yields the static average pressure in the reservoir drainage area, $\bar{p}$. If the production rates are known at various reservoir pressures, extrapolation into the future is possible.

Matthews and Russell [15] state the theoretical basis for the pressure buildup test by the following relation for an infinite boundary reservoir (nomenclature in Table 2).

$$p_{ws} = p_i + (q\mu/4\pi kh)\ln(\gamma^*\phi\mu c r_w^2/4k(t+\Delta t)) - (q\mu/4\pi kh)\ln(\gamma^*\phi\mu c r_w^2/4k\Delta t) \qquad (6)$$

where p_{ws} = well pressure after shut-in

p_i = initial pressure

t = time during well production

Δt = time after well is closed-in

γ^* = Euler's constant, 1.78

Table 2. Practical and Darcy Units

Parameter	Practical Units	Darcy Units
t, time	hr	sec
r, distance in radial direction	ft	cm
q, production rate	barrels/day (B/D)	cc/sec
p, pressure	psi	atm
μ, fluid viscosity	centipoise (cp)	cp
k, formation permeability	millidarcy (md)	darcies
h, formation thickness	ft	cm
ϕ, formation porosity	-	-
c, fluid compressibility	vol/vol/psi	vol/vol/atm
r_w, well radius	ft	cm

adapted from [16]

From the law of logarithms equation (6) then reduces to

$$p_{ws} = p_i - (q\mu/4\pi kh)\ln((t+\Delta t)/\Delta t) \quad (7)$$

By applying the common logarithm and converting into practical units (Table 2) equation (7) becomes

$$p_{ws} = p_i - (162.6q\mu B/kh)\log_{10}((t+\Delta t)/\Delta t) \quad (8)$$

where B = formation volume factor

Matthews and Russell [15] reported that an equation written for pressure behavior in an infinite reservoir may be immediately rewritten for a finite reservoir by substituting p^* for p_i. The variable p^* is defined as the well pressure at an infinite shut-in time, $(t+\Delta t)/\Delta t = 1$. Thus for a finite reservoir, a pressure buildup curve will decrease after a lengthy time period, as shown in Figure 4. The flattened curve approaches the average pressure, $\bar{p}$, in the bounded reservoir. The straight line portion of the bounded reservoir reaches the value of p^* at $(t+\Delta t)/\Delta t = 1$. In practice, a well will not be closed-in long enough to attain the condition represented by the flattened portion of the curve, but it is possibie to estimate $\bar{p}$ from the extrapolated value of p^*.

Matthews, Brons, and Hazebroek [17] developed equations for $(p^*-\bar{p})$ versus time for drainage areas of various shapes. A plot of $(p^*-\bar{p})/(70.6q\mu\phi B/kh)$ versus $0.000264kt/\phi\mu cA$ for various locations of a well in a square boundary is shown in Figure 5. The quantity A is the reservoir area in ft^2. Plots of various boundary shapes and well locations are available [17].

The recommended procedure for determining the average pressure is as follows:

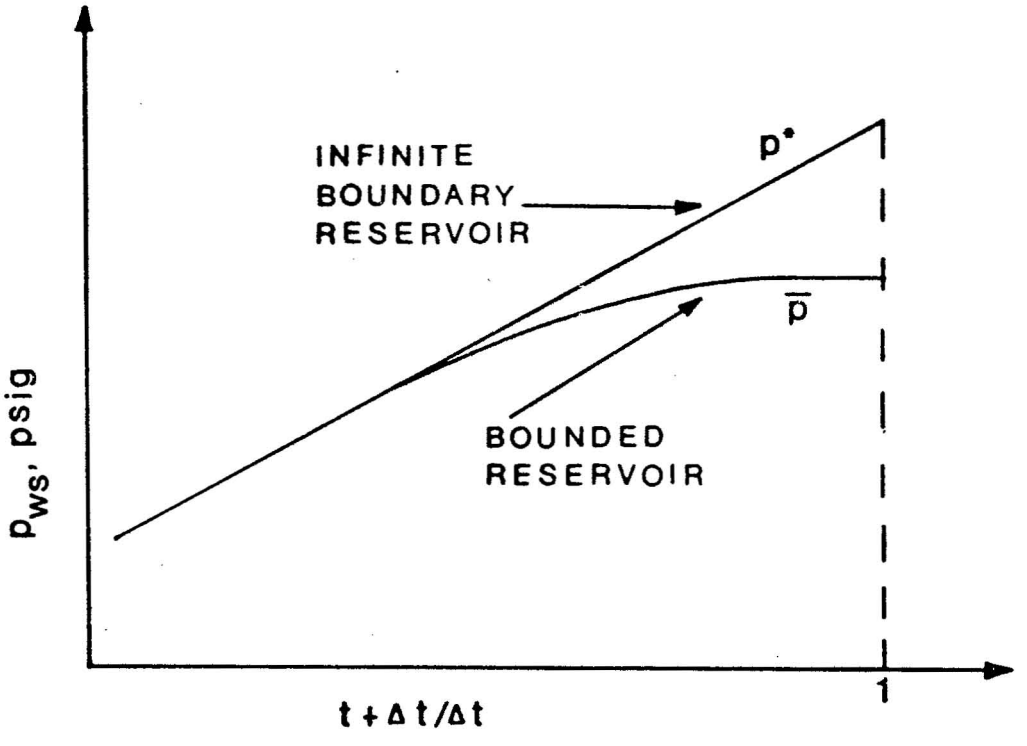


Figure 4. Pressure Buildup Curve for Infinite and Finite Boundary Reservoir [16]

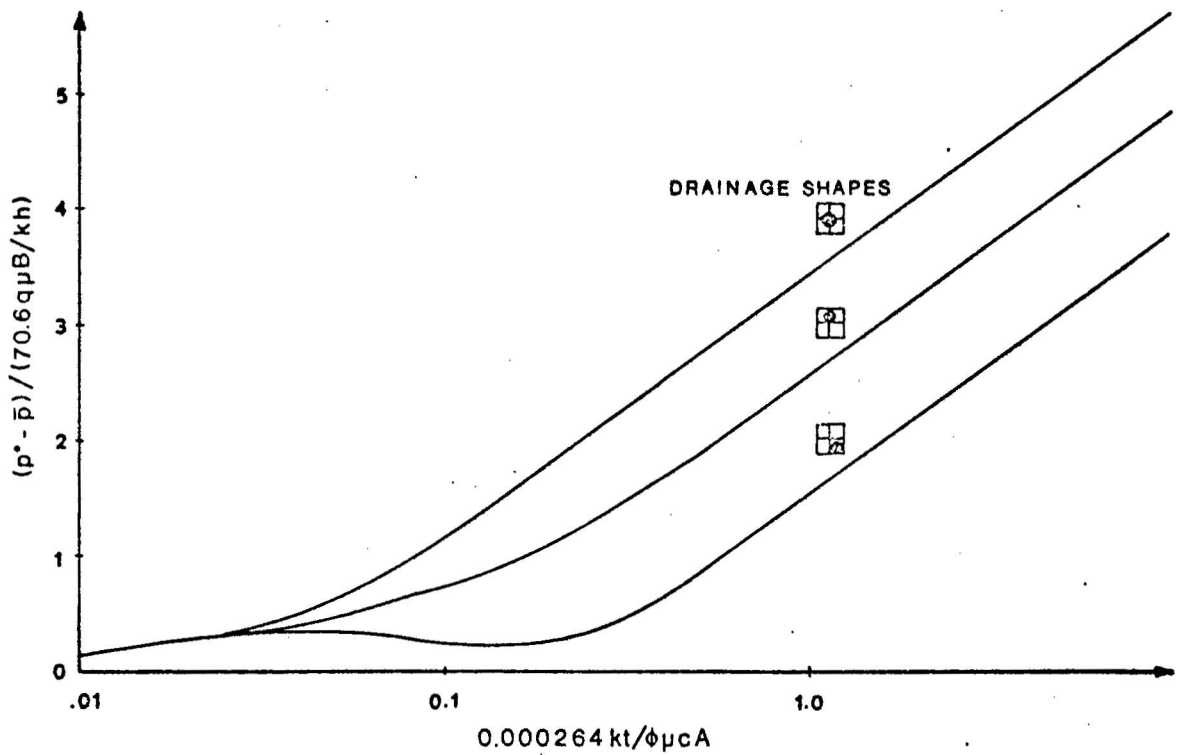


Figure 5. Pressure Function for Different Well Locations in a Square Boundary [17]

1. Plot p_{ws} versus $\log_{10}((t+\Delta t)/\Delta t)$ to determine p^* at infinite shut-in time. The graph is extrapolated to the point where $(t+\Delta t)/\Delta t = 1$ as illustrated in Figure 6.
2. t_{DA} is calculated from the following equation

$$t_{DA} = 0.000264kt/\phi\mu cA \qquad (9)$$

3. Use a pressure function plot, like Figure 5, with the appropriate drainage area and well location. Since p^* is known, calculate $\bar{p}$.

It should be noted that to obtain a single $\bar{p}$ value, there must be production for at least one month followed by a shut-in and buildup test, which will require about half a month. Therefore, it may be six to twelve months before performance prediction can be attempted with any confidence.

III.5. Hot-Water and Steam Properties

Geothermal fluids may contain salt, silica, calcium carbonate, potash, manganese, boron, iodine, bromine, lithium, sulfur, fluorine, potassium, arsenic, antimony, and other dissolved solids [18]. Dry steam reservoirs also produce non-condensable gases along with steam. The gases include carbon dioxide, hydrogen sulfide, ammonia, methane, and ethane. The presence of these non-condensable gases in a dry steam reservoir will affect the thermodynamic and transport properties of the produced fluid. Unfortunately, almost no experimental work seems to have been done on the properties of dry steam and non-condensable gas mixtures [13].

Ken Mashima [16]reported that the salt water content of the under-

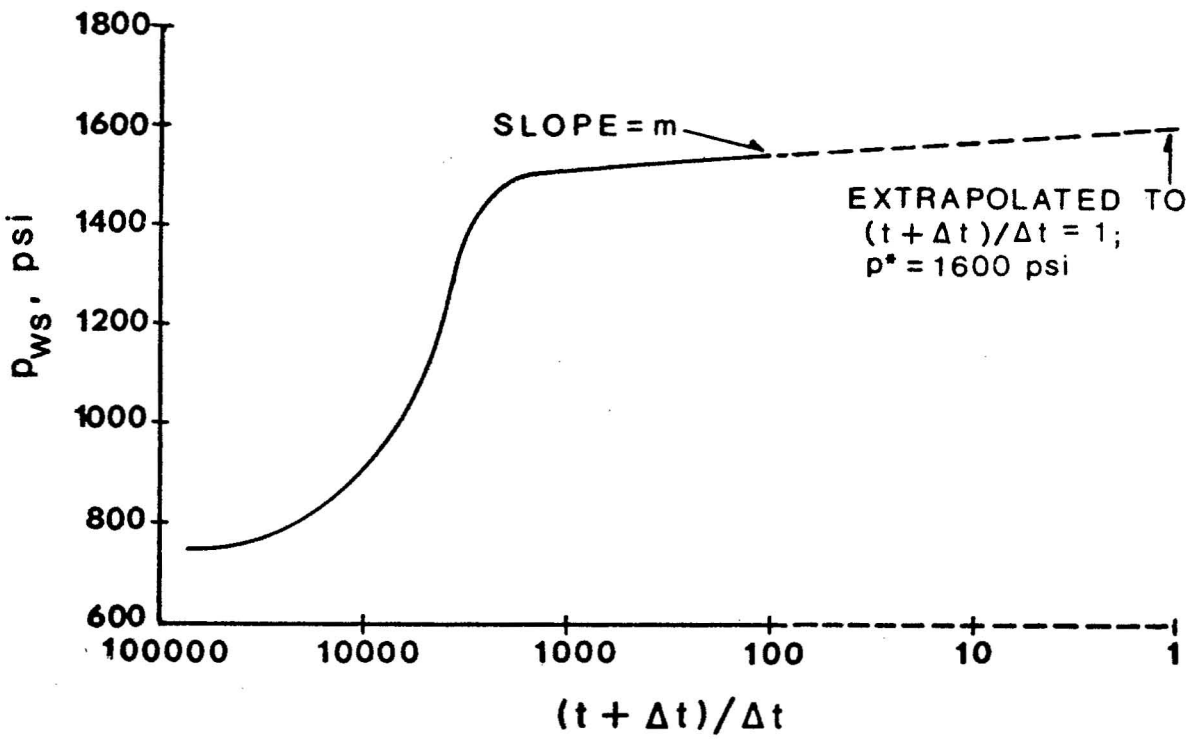


Figure 6. Sample Plot of Pressure Buildup Test [16]

ground water at Wairakei reservoir was less than 3% and the properties of dilute saline solutions are very close to the properties of pure water. However, Imperial Valley has as much as 30% dissolved solids by weight in the geothermal fluid [19].

Keeping this in mind, the true vapor pressure of water in a geothermal system may not necessarily be that presented in the steam tables. For a fixed pressure, the boiling temperature of water will be elevated by the presence of impurities mentioned above. However, this effect is usually rather small. The difference according to Ramey [13], would probably not be measurable in a vapor-dominated geothermal system.

Based on the data in the literature, Chou [20] formulated the interpolated formulas for vapor pressure, specific volume, enthalpy, and heat of vaporization of ordinary sea water in the temperature range of 32°F to 392°F for salinities of 0 to 120 ppt (parts per thousand). In Figures 7, 8, 9, and 10 are represented the effect of different salt water concentrations on these thermodynamic properties. The vapor pressure differences vary slightly for low salt concentrations and increase with higher salt concentrations (Figure 7). Specific volume is affected by the salt concentration as shown in Figure 8. The addition of salt results in a shift of pure water curve to the left. The greater the salt concentration, the greater the curve will shift. Figure 9 shows that the enthalpy value is lowered by the presence of salt. Heat of vaporization is only affected by salt concentrations at high temperatures (Figure 10). One trend observed is that the deviation from the pure water curve increases at higher temperatures.

Although the effect of salts in solution and the lowering of vapor

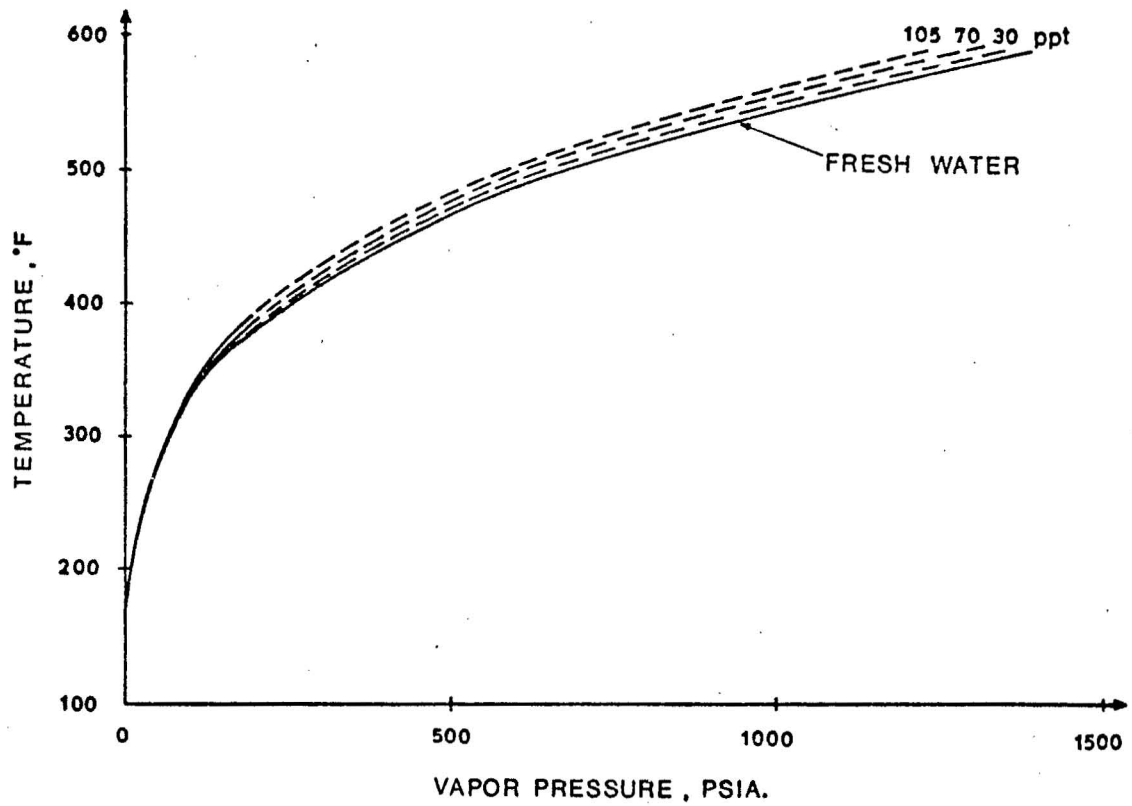


Figure 7. Effect of Salt on Vapor Pressure [16]

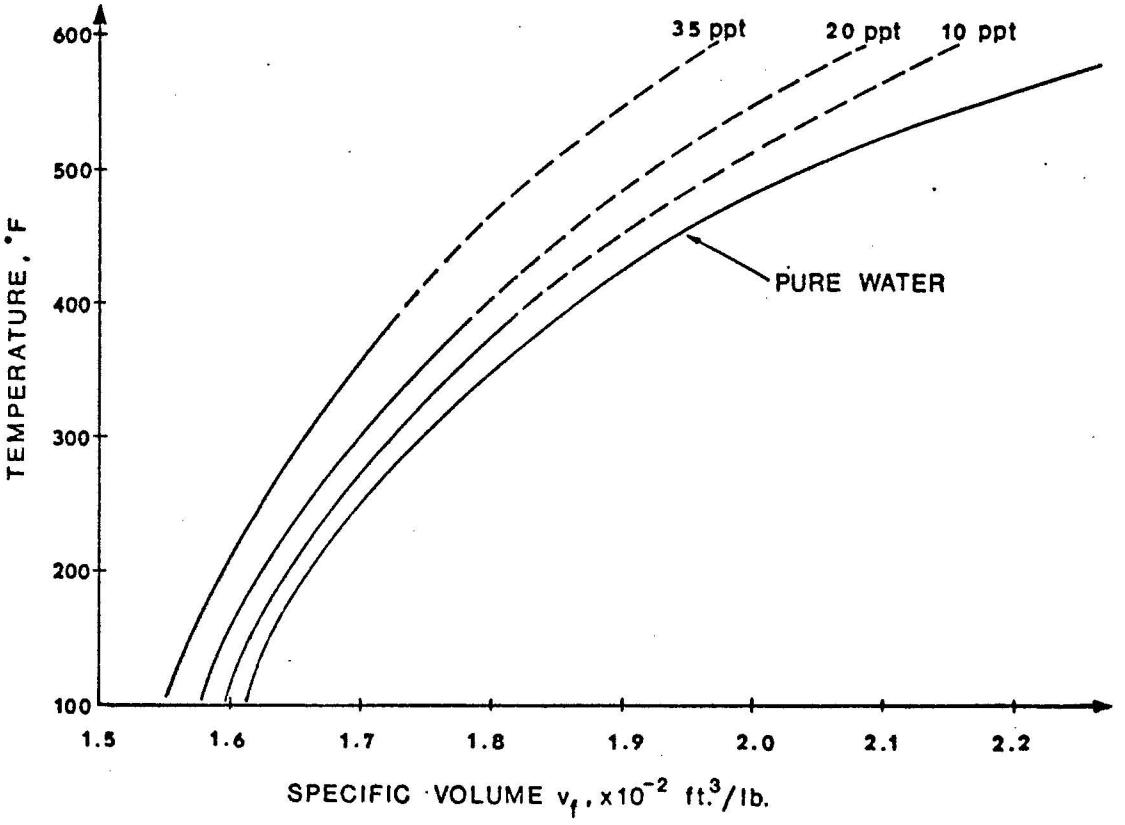


Figure 8. Effect of Salt on Specific Volume of Saturated Liquid [16]

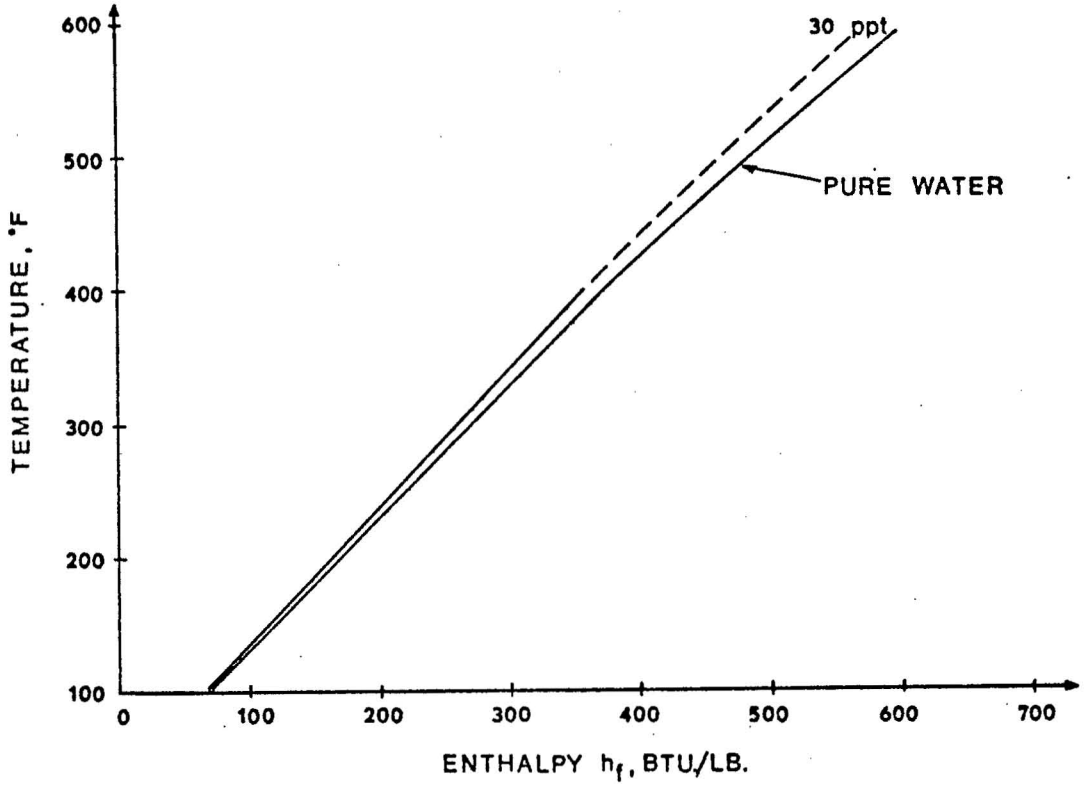


Figure 9. Effect of Salt on Enthalpy of Saturated Liquid [16]

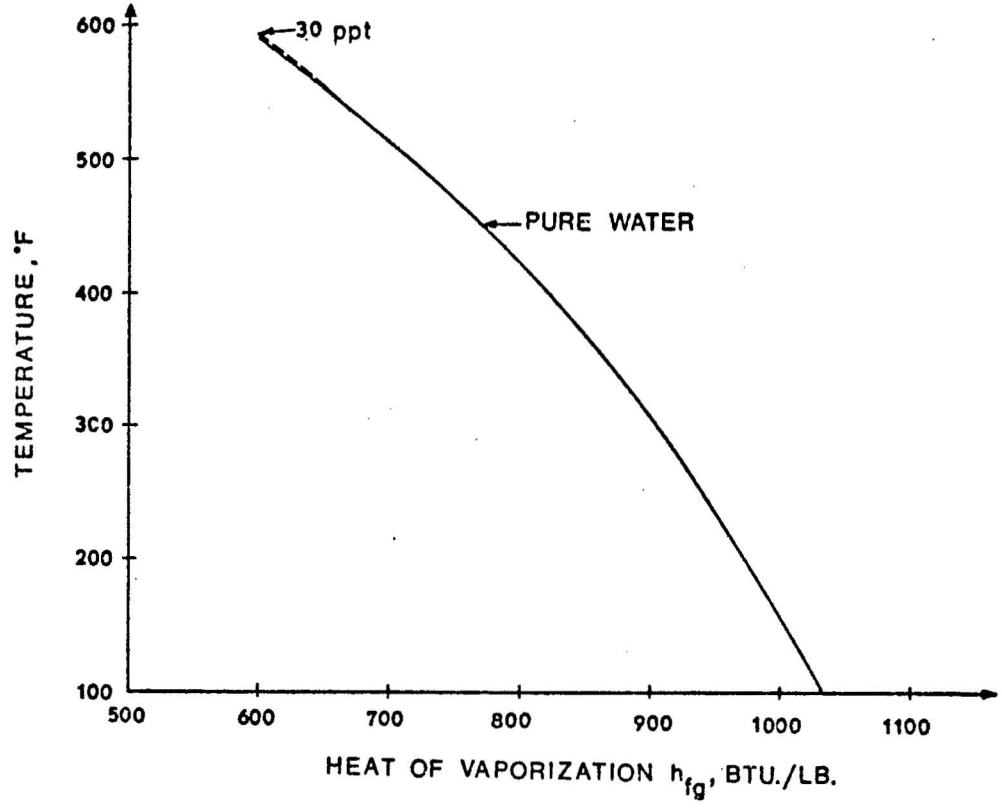


Figure 10. Effect of Salt on Heat of Vaporization [16]

pressure due to capillary pressure could have modifying influences upon quantitative calculations, the presence of salts should not alter the general principles presented.

In Hawaii, it is expected that the geothermal reservoir will be liquid dominated and brackish [16]. Therefore, as ocean water has a salt content of 19 ppt (parts per thousand) and if 1% encroachment can be assumed, then a relatively pure water condition exists. Even if the geothermal fluid approximates seawater, the effects of the salt content on the thermodynamic properties of water and steam can be effectively neglected.

III.6. Specific Heat of Formation

Dr. Gordon A. MacDonald [21] of the Hawaii Institute of Geophysics stated that the rock in the Hawaii geothermal reservoir would probably be basalt. A general equation of rock heat capacity was formulated from information obtained from Dr. MacDonald. In Figure 11 is displayed the general heat capacity equation for basalt in comparison with Ramey's [13] reported general heat capacity equation for other reservoir materials. The heat capacity of basalt in this case is higher than the heat capacity of sandstone, silty sand, siltstone, or shale.

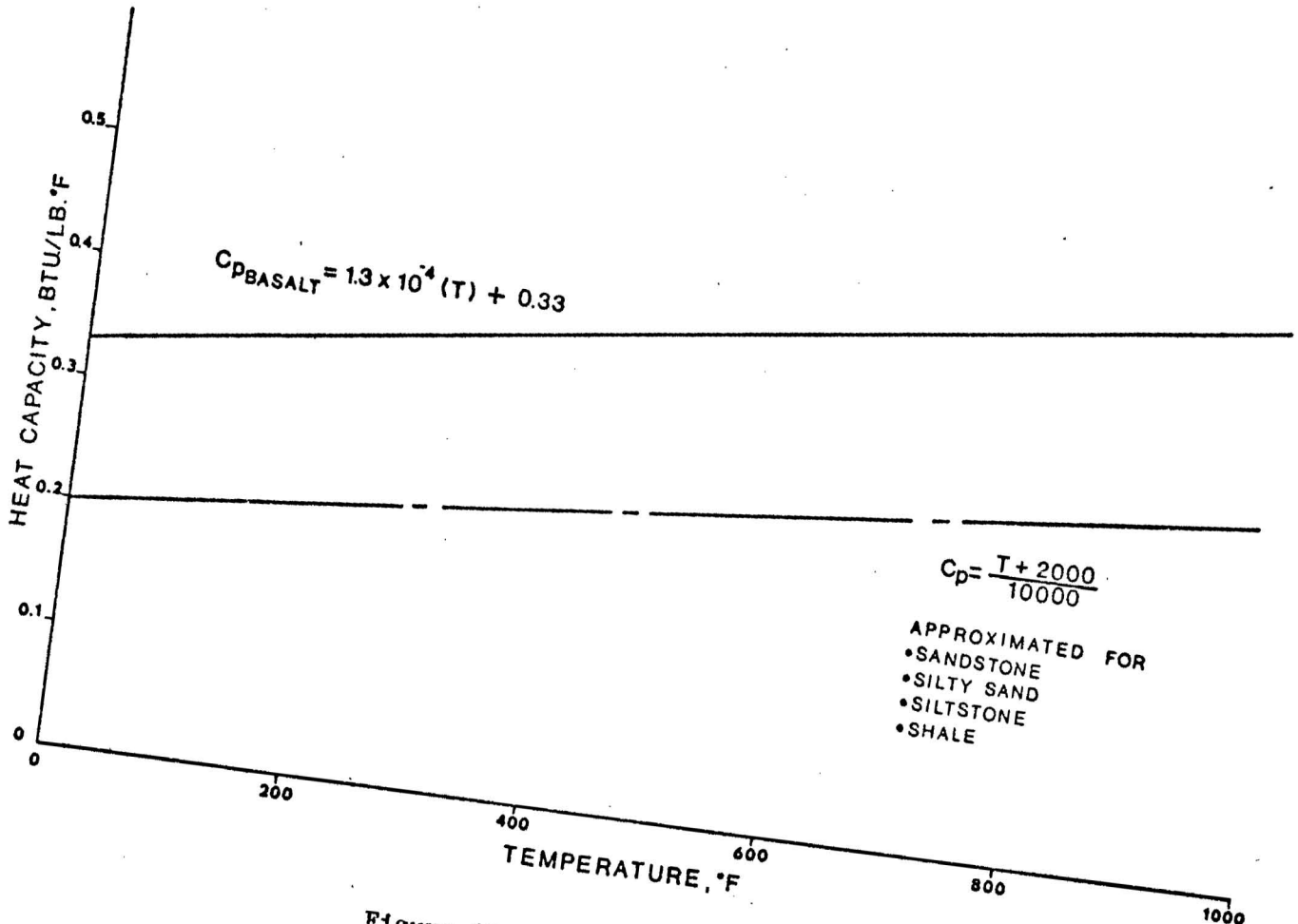


Figure 11. Heat Capacity Comparison

IV. FORMULATION OF COMPUTER MODEL

IV.1. Performance Matching and Prediction

The four basic equations (1), (2), (3), and (4) introduced in the previous chapter, in addition to the following assumptions about the reservoir and its conditions, are the basic foundation for this study.

1. The system is the fluid and rock in the reservoir at bulk volume, including the well.
2. Complete thermodynamic equilibrium exists.
3. Isothermal depletion in the single-phase reservoirs during production.
4. The reservoir contains essentially pure water.
5. Mass influx, W_e, is treated as a single parameter. The mass influx was considered a saturated liquid at a constant influx temperature, T_e.
6. Thermal and hydraulic equilibrium exists in the reservoir. Heat conducted to the bottom of the reservoir is equal to heat conducted to the top of the reservoir. This balance is only upset by production resulting in significant reservoir temperature change. Nevertheless, the heat conduction would be at such a slow rate that projection would not be affected.
7. Enthalpy produced, enthalpy lost, and current enthalpy are assumed to be equal ($H_p = H_L = H_c$). Heat loss in the well bore is neglected.
8. Heat capacity at constant pressure is essentially the same

as at constant volume.

Some of the preceding assumptions were adapted from Whiting and Ramey [4].

The operation of matching the past performance data using the material-energy balance to determine the initial conditions involve a least squares fitting technique. Basically, the calculated pressure is matched against the actual average pressure with time as represented by the cumulative production figures (Plots presented in V. Results and Discussion). The mass influx is initially considered negligible. A range of least squares fits are made by varying combinations of the unknown initial conditions. Once the optimum initial parameters are known, mass influx may be varied until the maximum allowable rate (i.e. largest possible mass influx rate that has a good curve fit) is determined. In the two-phase case influx temperature may be altered also. A least squares value of zero means a perfect fit has been obtained.

An optimization scheme BOX (Optimization scheme explained in IV.2.1. Description of Computer Program BOX and BOX User's guide, listing, and printout in Appendix D) is employed to find the optimum initial conditions by minimizing the least squares function.

$$S = \sum^{N}(P_{actual}-P_{calc})^2 \qquad (10)$$

where S = least squares value

P_{actual} = actual average reservoir pressure, psia

P_{calc} = calculated pressure, psia

N = number of past performance data sets (data set = actual average reservoir pressure versus cumulative mass produced)

The initial parameters to be optimized in the three different cases are:

1. Compressed liquid reservoir
    a. Initial pressure, P_i
    b. Initial mass, W_i
2. Saturated liquid-steam reservoir
    a. Initial temperature, T_i
    b. Initial mass, W_i
    c. Initial steam quality, X_i
3. Superheated steam reservoir
    a. Initial (pressure/compressibility factor), P_i/Z_i
    b. Initial mass, W_i

Chen [22] reported that the initial conditions obtained from performance matching may or may not be the real reservoir condition. Nevertheless, it is not important to have the correct model as long as the performance of the model and the reservoir are the same.

When the optimum initial conditions are known, computer program PRE (Program explained in IV.2.2. Description of Computer Program PRE and PRE User's guide, listing, and printout in Appendix E) can be used to predict the performance at different production rates. A thirty-year projection, which is standard in the utility field, was used.

IV.1.1. Saturated Liquid-Steam Reservoir Calculation Scheme

The calculation scheme for this case compared to the other two cases is the most rigorous. Specifically, the current steam quality is calculated from the volumetric balance.

$$X_c = ((V\phi/W_c)-V_f)/(V_g-V_f) \tag{11}$$

The current enthalpy is solved from the enthalpy equation.

$$H_c = (1-X_c)H_f + H_g \tag{12}$$

Now setting the energy balance to zero, the current temperature that satisfies equation (13) can be found.

$$Y = W_iH_i - W_pH_p + W_eH_e - W_LH_L + V(1-\phi)\rho_rC_r(T_i-T_c) + Q_s - W_cH_c \tag{13}$$

Once the current temperature is known, the corresponding pressure can be determined. From a set of past performance data, a set of calculated pressures are found for the least squares fit. In Figure 12 is the route necessary to obtain the optimum initial conditions.

IV.1.2. Compressed Liquid Reservoir Calculation Scheme

The compressed liquid reservoir equation is a reduced case of the mass-energy-volumetric balance equations used in the two-phase case (Calculations presented in Appendix A). The reduced equation is in effect a mass-volumetric relationship.

$$V_L = V_{Li}/(1 + (W_e/W_i) - (W_p/W_i) - (W_L/W_i)) \tag{14}$$

where V_L = specific volume of liquid water, ft^3/lb

V_{Li} = specific volume of liquid water at initial conditions, ft^3/lb

From the above equation, only the initial liquid specific volume and the various mass data are needed to determine the current liquid specific volume. Subprogram WASP (Program explained in IV.2.3. Description of Subprogram WASP and WASP User's guide in Appendix F) then is used to calculate the current pressure for the evaluation of the least squares value. A set of calculated pressures will be obtained from each set of

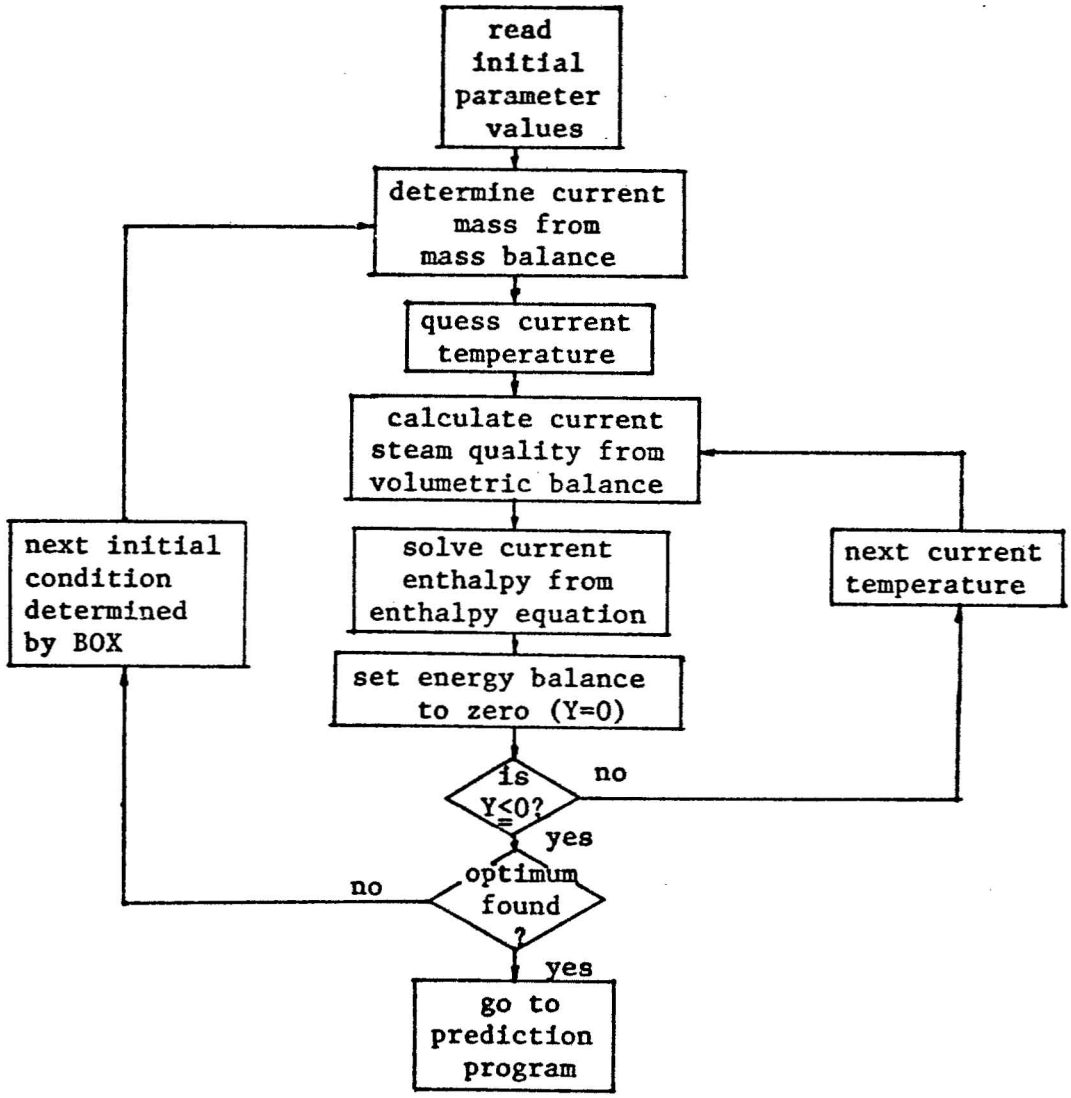


Figure 12. Saturated Liquid-Steam Reservoir Calculation Scheme

production data.

IV.1.3. Superheated Steam Reservoir Calculation Scheme

The superheated steam reservoir case is similar to the compressed liquid reservoir case. Since steam is a gas, the static reservoir pressure is handled in the usual gas reservoir engineering manner. This is based upon the mass balance equation (1) and a volumetric balance, which specifies that the volume of gas produced must equal the original mass of gas from the original pressure to the current pressure.

$$W_p V_v = W_i (V_v - V_{vi}) + W_e V_v - W_p V_v \qquad (15)$$

where V_v = specific volume of vapor, ft^3/lb

V_{vi} = specific volume of vapor at initial conditions, ft^3/lb

The specific volume terms, which is a function of temperature and pressure, can be expressed by the real gas law. In Figure 13 is shown the relationship of compressibility factor as a function of temperature and pressure.

$$V_v = ZRT/pM \qquad (16)$$

where Z = compressibility factor

R = gas law constant, 10.73 $(psia\text{-}ft^3)/(lb_{mole}\text{-}\,^\circ R)$

T = reservoir temperature, °R

M = molecular weight of steam, 18 lb/lb_{mole}

p = reservoir pressure, psia

Substituting equation (16) into (15) and rearranging results in,

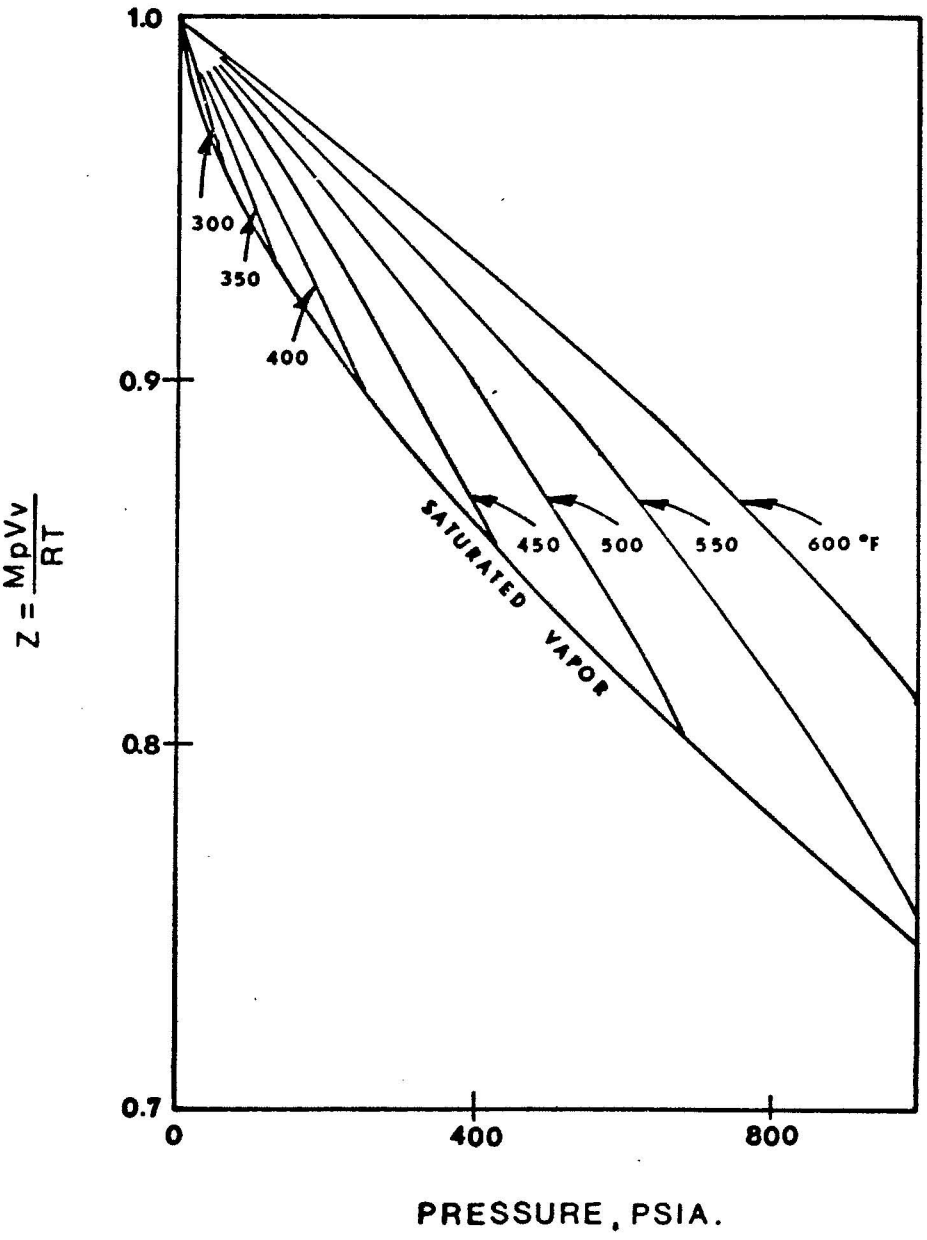


Figure 13. Gas Law Deviation Factor for Steam [23]

$$P/Z = (P_i/Z_i)(1 + (W_e/W_i) - (W_p/W_i) - (W_L/W_i)) \quad (17)$$

where P_i/Z_i = initial (pressure/compressibility factor), psia

which is similar to the compressed liquid case. Only the various mass data and the initial (pressure/compressibility factor) are needed to obtain the current pressure and ultimately the least squares value.

Ramey [23] reported that if the actual field data is plotted (P/Z versus W_p) and a straight line results, the reservoir can be considered closed with no recharge. This straight line may be extrapolated to the abandonment pressure level to provide a measure of the ultimate recovery of steam. An extrapolation of zero pressure yields a measure of the initial mass of steam in place, W_i. Water influx usually results in a concave-upwards shape in the plot and pressure often stabilizes after a length of time.

IV.2. Computer Analysis

Basically, the computer analysis consists of two separate programs: BOX and PRE. The BOX program is primarily an optimization scheme that minimizes the least squares function (performance matching) and locates the optimum initial parameters for a compressed liquid, saturated liquid-steam, or superheated steam reservoir. Program PRE is used to predict the thirty-year performance of the geothermal reservoir at various production rates.

The use of BOX requires the user to supply the estimated range (i.e. upper and lower constraints) of each initial parameter. As it turns out, the success of finding the minimum least squares value (good performance

match) and subsequent optimum initial parameters is highly dependent on the constraints chosen. Therefore, the general scheme for obtaining a good match is to vary the constraints. The frequent use of BOX (BOX has about 600 cards and PRE over 825 cards) prior to the use of PRE is the reason why these two programs were not incorporated into one.

IV.2.1. Description of Computer Program BOX

This program can be used to determine the minimum of a multivariable, nonlinear function subject to nonlinear inequality constraints.

$$\text{Minimize} \quad -F = \sum^{JK}(PBAR_i - PC_i)^2 \tag{18}$$

where PBAR = actual average reservoir pressure

PC = calculated pressure

i = 1, 2,...,JK

JK = number of past production data sets

$$\text{Subject to} \quad G_K \leq X_K \leq H_K$$

where G_K = lower constraint

H_K = upper constraint

K = 1, 2,...,M

M = number of constraints

The implicit variables, X_{N+1} ,...,X_M, are dependent functions of the explicit independent variables X_1, X_2,...,X_N (where N = number of unknown initial parameters). The upper and lower constraints are either constants or functions of the independent variables.

The optimization scheme is based on the "complex" method developed

by M.J. Box [24]. This method is a sequential search technique which has proven to be effective in solving problems with nonlinear objective functions subject to nonlinear inequality constraints. No derivatives are required. The procedure can be used to determine the global minimum, as the initial set of points are randomly scattered throughout the feasible region. The "complex" algorithm proceeds as follows:

1. An original "complex" of KN =2N (for N<5) points are generated consisting of a feasible starting point and KN-1 additional points generated from random numbers and constraints for each of the independent variables:

$$X_{i,j} = G_i + r_{i,j}(H_i - G_i) \tag{19}$$

where $i = 1, 2, \ldots, N$

$j = 1, 2, \ldots, KN-1$

$r_{i,j}$ = random numbers between 0 and 1

2. The selected points must satisfy both the explicit and implicit constraints. If at any time the explicit constraints are violated, the point is moved a small distance δ (violation correction parameter) inside the violated limit. If an implicit constraint is violated, the point is moved one half of the distance to the centroid of the remaining points,

$$X_{i,j}(\text{new}) = (X_{i,j}(\text{old}) + \bar{X}_{i,c})/2.0 \tag{20}$$

where the coordinates of the centroid of the remaining points $\bar{X}_{i,c}$, are defined by:

$$\bar{X}_{i,c} = (1/KN-1)\left(\sum_{j=1}^{KN} X_{i,j} - X_{i,j}(\text{old})\right) \tag{21}$$

This process is repeated as necessary until all the implicit constraints are satisfied.

3. The objective function (least squares function) is evaluated at each point. The point having the lowest function value is replaced by a point which is located at a distance α (reflection factor) times as far from the centroid of the line joining the rejected point and the centroid:

$$X_{i,j}(\text{new}) = (\bar{X}_{i,c} - X_{i,j}(\text{old})) + \bar{X}_{i,c} \qquad (22)$$

Box [24] recommends a value of $\alpha = 1.3$

4. If a point repeats in giving the lowest function value on consecutive trials, it is moved ½ the distance to the centroid of the remaining points.
5. The new point is checked against the constraints and is adjusted as before if the constraints are violated.
6. Convergence is assumed when the objective function values at each point are within β (convergence parameter) units for γ (convergence parameter) consecutive iterations. An iteration is defined as the calculations required to select a new point which satisfies the constraints and does not repeat in yielding the lowest function value.

The preceding discussion was adapted from Kuester and Mize [25]. A flow chart illustrating the general optimization scheme is given in Figure 14.

Subroutine FUNK contains the objective function that is to be minimized. A set of independent variables (initial parameter) are transferred to this subroutine in an attempt to match the past performance of

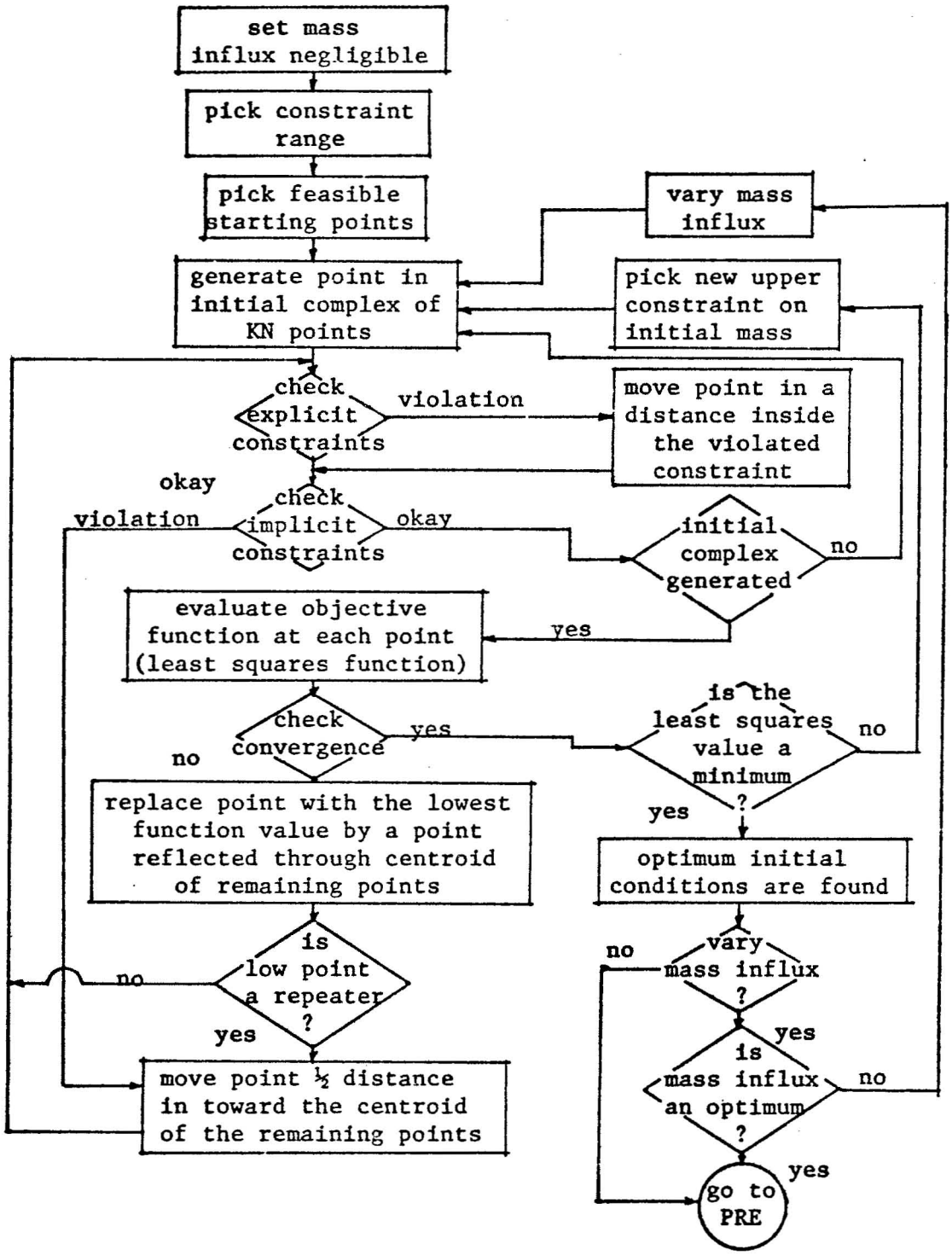


Figure 14. BOX Optimization Scheme (adapted from [25])

the geothermal reservoir. The three geothermal reservoirs considered are compressed liquid, saturated liquid-steam, and superheated steam. A flow chart of the general scheme is shown in Figure 15.

IV.2.2. Description of Computer Program PRE

This computer program is used to make a thirty-year projection of the performance for a geothermal reservoir, whether it be compressed liquid, saturated liquid-steam, or superheated steam. It can also be used to determine the effects of phase changes (e.g. the path from a single-phase region entering the two-phase region). The calculation scheme is as follows:

1. The optimum initial conditions determined from BOX are read into PRE.
2. These values are used in the material-energy balance equation to match the performance of the geothermal reservoir. If a phase change occurs during the performance matching, the user must remove the appropriate production data so the performance matching will end prior to the transition point, readjust the computer parameters, then start again.
3. Thirty-year projections are made at different production rates. In the event a phase change occurs during the predictions, the common boundary or transition point is determined. Once found, projections are continued until the thirty-year mark is reached, the reservoir pressure falls below 60 psia, or no current mass exists. In Figure 16 is displayed the general logic of program PRE.

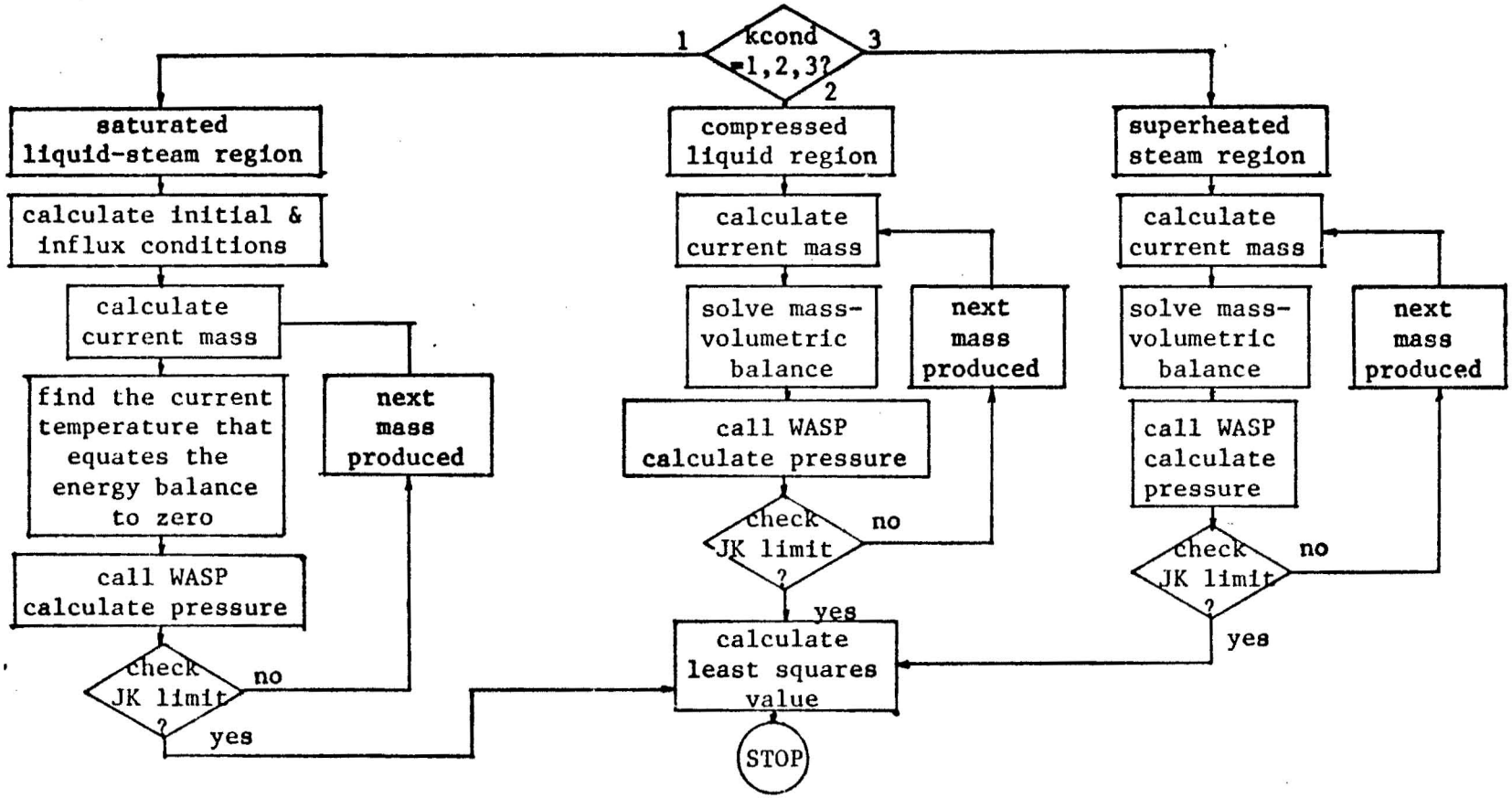


Figure 15. BOX - Subroutine FUNK Logic Diagram

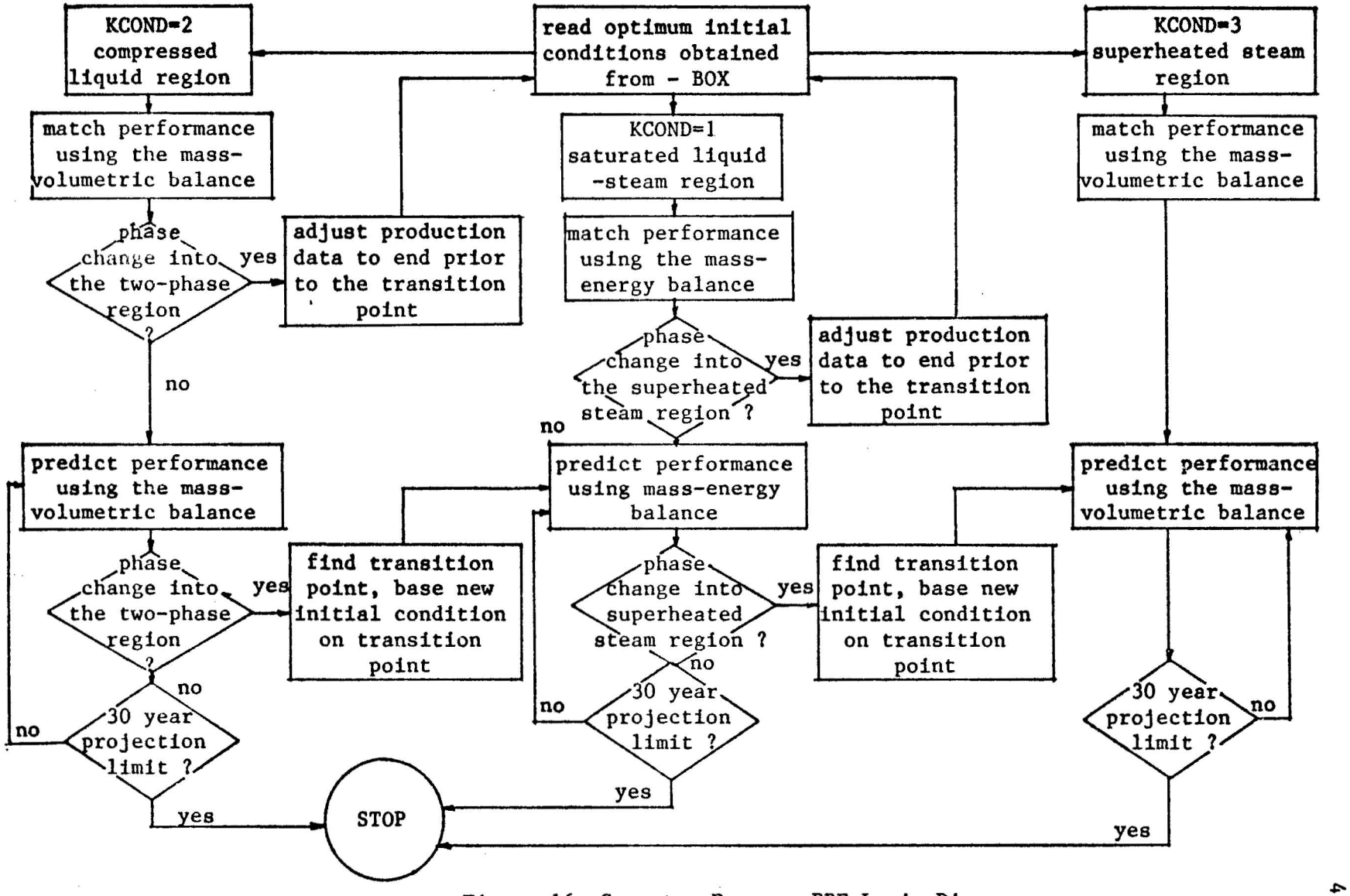


Figure 16. Computer Program PRE Logic Diagram

IV.2.3. Description of Subprogram WASP

WASP [26] is used to calculate the thermodynamic and transport properties of water and steam. It accepts any combination of pressure, temperature, or density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. The properties available in any combination as output include temperature, pressure, density, entropy, enthalpy, specific heats (C_p and C_v), sonic velocity, $(\partial P/\partial \rho)_T$, $(\partial P/\partial T)_\rho$, viscosity, thermal conductivity, surface tension, and the Laplace constant (WASP User's guide in Appendix F).

IV.3. Error Analysis

The convergence parameters of BOX are easily calculated (parameters defined in Appendix D). These values are multiples of either the function value or the independent variable values. Theoretically, a perfect fit will have a least squares value of zero. However, in the BOX program the calculated least squares value is truncated to an integer, so a zero least squares value will be a close, although not perfect fit.

To enable the use of WASP to calculate the thermodynamic properties of water and steam with a high degree of accuracy, the subprogram is operated in double precision. BOX and PRE, which make frequent calls to WASP, are also in double precision. In order to check for any discrepancies, the authors of WASP [26] made comparison plots of temperature, pressure, and density using the International Skeleton Tables for steam and water [27,28] as their references. Plots are in Appendix B.

Figure 34 represents the percent error in density as a function of density. With the exception of three points, all the values are within

+0.25 and -0.50 percent and generally have an error of less than 1 part in 3000. The error could be reduced by tightening the convergence criteria, however, this is not recommended because of the increased computer time and cost.

The relative error in pressure versus pressure is displayed in Figure 35. In all cases the calculated pressures are within +3.0 and -2.0 percent of the tabulated values. Most of the points lie within the $\pm$0.25 percent range. The prediction of pressure at high density (low temperature), using a fundamental equation or a state equation, is quite difficult, yet these errors are all within accepted tolerances.

The final comparison plot done with WASP (Figure 36) is the percent relative error of temperature versus temperature. With the exception of about a dozen points, the predicted temperatures are within +0.25 and -0.40 percent, lying generally in the $\pm$0.10 percent range.

Usually temperature and density are predictable because of the manner in which data was acquired, however, pressure is always difficult to calculate. With these basic guidelines in mind, a faithful representation of the International Skeleton Tables was made [26].

WASP appears in subroutine FUNK of both BOX and PRE quite frequently. In the two-phase section of each program, WASP was contained within a do-loop that conservatively made over 13,000 calls to WASP. This resulted in excessive computer time and extreme expense. To reduce the cost, general equations (36),(37),(38), and (39) (equations presented in Appendix G) for the desired thermodynamic properties were determined by linear regression. Keenan and Keyes' tabulated steam tables [29] was used as the reference for the chosen temperature range of 300°F to 600°F.

In Figure 37 is represented the percent relative error of enthalpy of saturated liquid (H_f) versus temperature. Except for five points at the temperature limits, the enthalpies are within $\pm$0.1 percent. Considering all the points, the range of +0.1 to -0.16 percent is still very good. The percent relative error of the enthalpy of saturated vapor (H_g) versus temperature was within $\pm$0.1 percent (Figure 38), while the specific volume of saturated liquid (V_f) versus temperature ranged from +0.3 to -0.2 percent (Figure 39).

The last thermodynamic property in question is the specific volume of saturated vapor (V_g) presented in Figure 40. The range of error was from +0.6 to -0.4 percent. The percent error is relatively high compared to the other three plots, but still within WASP's maximum relative error of 3.0 percent.

Re-examining Figures 37, 38, 39, and 40 it can be seen that the thermodynamic values at the upper extreme temperatures have the largest percent relative error. This was expected since temperature approaches the critical point (705.5 °F).

V. RESULTS AND DISCUSSION

This section is divided into three parts. The first part concerns the performance matching results, the second part concerns the results of the performance predictions, and the final part concerns the sensitivity analysis of the reservoir and BOX parameters.

Reservoir performance data to test each case was difficult to obtain because private firms generally treat reservoir data as proprietary. However, with assistance from Dr. James W. Mercer of the United States Geological Survey [30], five reels of microfilmed data from the Wairakei geothermal field was secured. A second set of production data was obtained with the help of Dr. R.S. Bolton [31], chief geothermal engineer with the Ministry of Works and Development in New Zealand [32]. The third and final set of production data was found in a publication by Henry J. Ramey Jr. [23].

V.1. Performance Matching

In Table 3 is displayed the optimum initial conditions and minimum least squares value for the three geothermal reservoirs studied:compressed liquid, saturated liquid-steam, and superheated steam. Negligible mass influx and a large mass influx (determination of mass influx rate in V.3. Sensitivity Analysis) were two cases studied for each reservoir. The influx temperature was kept at 960°R throughout the entire matching analysis. For the reservoirs studied it appeared that large mass influx gave better curve fits. This was especially true for the compressed liquid case, in which the least squares value decreased from

Table 3. Optimum Initial Parameters of a Geothermal Reservoir

Reservoir Parameter	Without Mass Influx	With Mass Influx
Compressed Liquid:		
Initial Pressure	772.38813	773.879926
Initial Mass	$5.41981569 \times 10^{14}$	$4.87952480 \times 10^{14}$
Least Squares Value	105	80
Saturated Liquid-Steam:		
Initial Temperature	952.518912	952.739672
Initial Mass	$1.87592409 \times 10^{12}$	$1.77168640 \times 10^{12}$
Initial Steam Quality	0.078475	0.014552
Least Squares Value	8	4
Superheated Steam:		
Initial (Pressure/Compressibility Factor)	188.162590	191.32409
Initial Mass	2.3119401×10^{11}	1.8274845×10^{11}
Least Squares Value	0	0

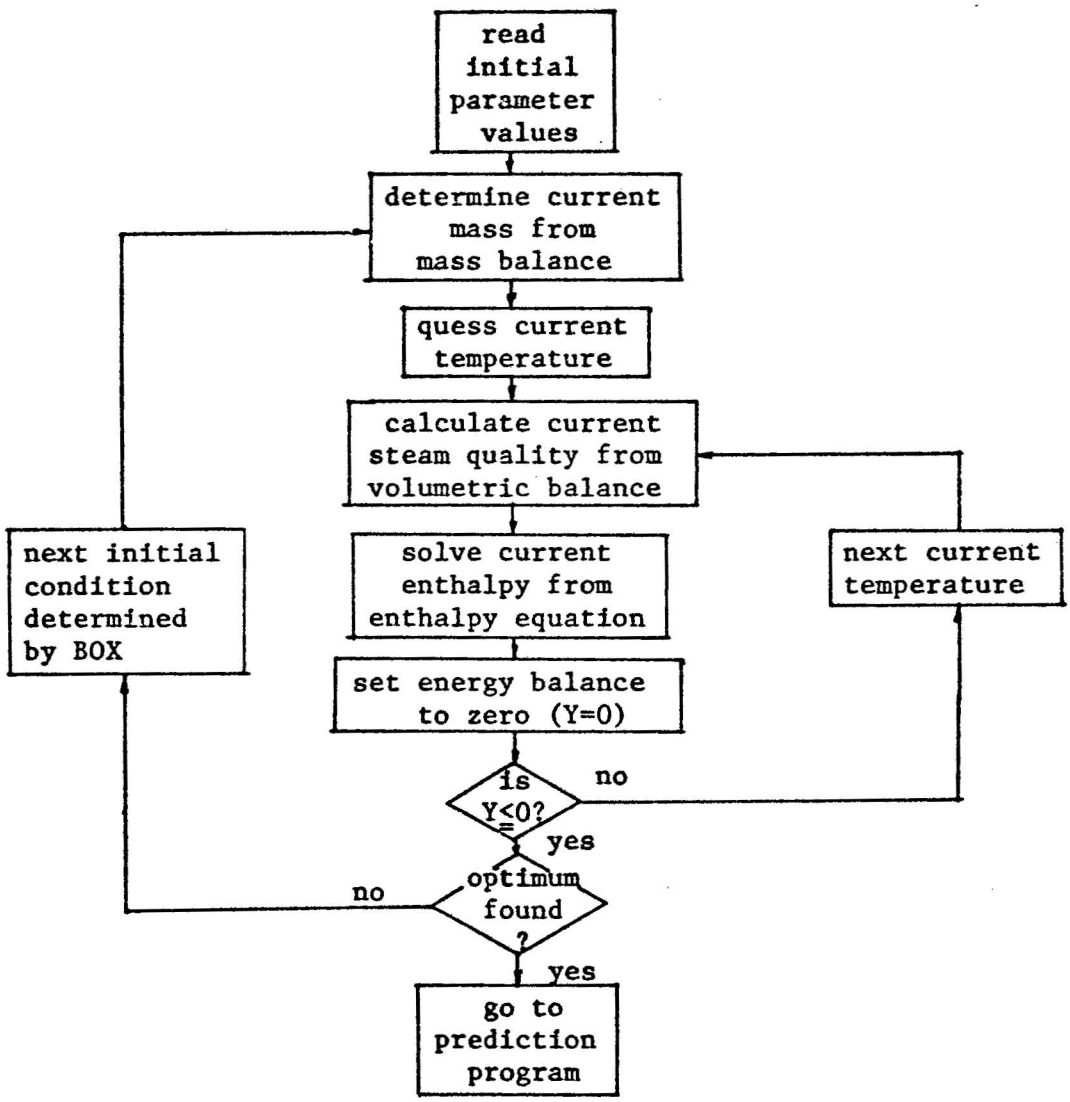


Figure 12. Saturated Liquid-Steam Reservoir Calculation Scheme

production data.

IV.1.3. Superheated Steam Reservoir Calculation Scheme

The superheated steam reservoir case is similar to the compressed liquid reservoir case. Since steam is a gas, the static reservoir pressure is handled in the usual gas reservoir engineering manner. This is based upon the mass balance equation (1) and a volumetric balance, which specifies that the volume of gas produced must equal the original mass of gas from the original pressure to the current pressure.

$$W_p V_v = W_i (V_v - V_{vi}) + W_e V_v - W_p V_v \qquad (15)$$

where V_v = specific volume of vapor, ft^3/lb

V_{vi} = specific volume of vapor at initial conditions, ft^3/lb

The specific volume terms, which is a function of temperature and pressure, can be expressed by the real gas law. In Figure 13 is shown the relationship of compressibility factor as a function of temperature and pressure.

$$V_v = ZRT/pM \qquad (16)$$

where Z = compressibility factor

R = gas law constant, 10.73 $(psia\text{-}ft^3)/(lb_{mole}\text{-}\,^\circ R)$

T = reservoir temperature, °R

M = molecular weight of steam, 18 lb/lb_{mole}

p = reservoir pressure, psia

Substituting equation (16) into (15) and rearranging results in,

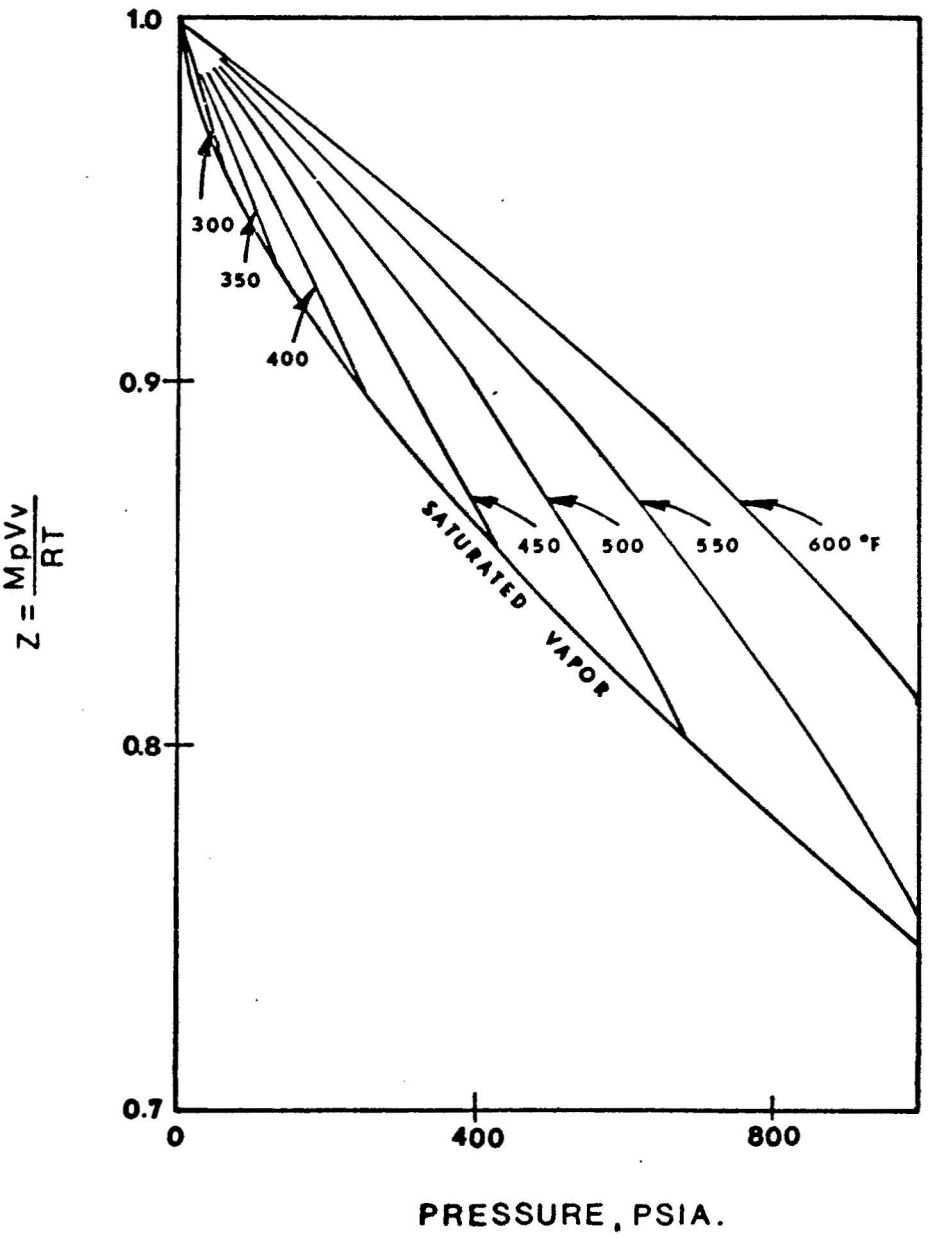


Figure 13. Gas Law Deviation Factor for Steam [23]

$$P/Z = (P_i/Z_i)(1 + (W_e/W_i) - (W_p/W_i) - (W_L/W_i)) \quad (17)$$

where P_i/Z_i = initial (pressure/compressibility factor), psia

which is similar to the compressed liquid case. Only the various mass data and the initial (pressure/compressibility factor) are needed to obtain the current pressure and ultimately the least squares value.

Ramey [23] reported that if the actual field data is plotted (P/Z versus W_p) and a straight line results, the reservoir can be considered closed with no recharge. This straight line may be extrapolated to the abandonment pressure level to provide a measure of the ultimate recovery of steam. An extrapolation of zero pressure yields a measure of the initial mass of steam in place, W_i. Water influx usually results in a concave-upwards shape in the plot and pressure often stabilizes after a length of time.

IV.2. Computer Analysis

Basically, the computer analysis consists of two separate programs: BOX and PRE. The BOX program is primarily an optimization scheme that minimizes the least squares function (performance matching) and locates the optimum initial parameters for a compressed liquid, saturated liquid-steam, or superheated steam reservoir. Program PRE is used to predict the thirty-year performance of the geothermal reservoir at various production rates.

The use of BOX requires the user to supply the estimated range (i.e. upper and lower constraints) of each initial parameter. As it turns out, the success of finding the minimum least squares value (good performance

match) and subsequent optimum initial parameters is highly dependent on the constraints chosen. Therefore, the general scheme for obtaining a good match is to vary the constraints. The frequent use of BOX (BOX has about 600 cards and PRE over 825 cards) prior to the use of PRE is the reason why these two programs were not incorporated into one.

IV.2.1. Description of Computer Program BOX

This program can be used to determine the minimum of a multivariable, nonlinear function subject to nonlinear inequality constraints.

$$\text{Minimize} \quad -F = \sum^{JK}(PBAR_i - PC_i)^2 \tag{18}$$

where PBAR = actual average reservoir pressure

PC = calculated pressure

i = 1, 2,...,JK

JK = number of past production data sets

$$\text{Subject to} \quad G_K \leq X_K \leq H_K$$

where G_K = lower constraint

H_K = upper constraint

K = 1, 2,...,M

M = number of constraints

The implicit variables, X_{N+1} ,...,X_M, are dependent functions of the explicit independent variables X_1, X_2,...,X_N (where N = number of unknown initial parameters). The upper and lower constraints are either constants or functions of the independent variables.

The optimization scheme is based on the "complex" method developed

by M.J. Box [24]. This method is a sequential search technique which has proven to be effective in solving problems with nonlinear objective functions subject to nonlinear inequality constraints. No derivatives are required. The procedure can be used to determine the global minimum, as the initial set of points are randomly scattered throughout the feasible region. The "complex" algorithm proceeds as follows:

1. An original "complex" of KN =2N (for N<5) points are generated consisting of a feasible starting point and KN-1 additional points generated from random numbers and constraints for each of the independent variables:

$$X_{i,j} = G_i + r_{i,j}(H_i - G_i) \tag{19}$$

where $i = 1, 2, \ldots, N$

$j = 1, 2, \ldots, KN-1$

$r_{i,j}$ = random numbers between 0 and 1

2. The selected points must satisfy both the explicit and implicit constraints. If at any time the explicit constraints are violated, the point is moved a small distance δ (violation correction parameter) inside the violated limit. If an implicit constraint is violated, the point is moved one half of the distance to the centroid of the remaining points,

$$X_{i,j}(\text{new}) = (X_{i,j}(\text{old}) + \bar{X}_{i,c})/2.0 \tag{20}$$

where the coordinates of the centroid of the remaining points $\bar{X}_{i,c}$, are defined by:

$$\bar{X}_{i,c} = (1/KN-1)\left(\sum_{j=1}^{KN} X_{i,j} - X_{i,j}(\text{old})\right) \tag{21}$$

This process is repeated as necessary until all the implicit constraints are satisfied.

3. The objective function (least squares function) is evaluated at each point. The point having the lowest function value is replaced by a point which is located at a distance α (reflection factor) times as far from the centroid of the line joining the rejected point and the centroid:

$$X_{i,j}(\text{new}) = (\bar{X}_{i,c} - X_{i,j}(\text{old})) + \bar{X}_{i,c} \qquad (22)$$

Box [24] recommends a value of $\alpha = 1.3$

4. If a point repeats in giving the lowest function value on consecutive trials, it is moved ½ the distance to the centroid of the remaining points.
5. The new point is checked against the constraints and is adjusted as before if the constraints are violated.
6. Convergence is assumed when the objective function values at each point are within β (convergence parameter) units for γ (convergence parameter) consecutive iterations. An iteration is defined as the calculations required to select a new point which satisfies the constraints and does not repeat in yielding the lowest function value.

The preceding discussion was adapted from Kuester and Mize [25]. A flow chart illustrating the general optimization scheme is given in Figure 14.

Subroutine FUNK contains the objective function that is to be minimized. A set of independent variables (initial parameter) are transferred to this subroutine in an attempt to match the past performance of

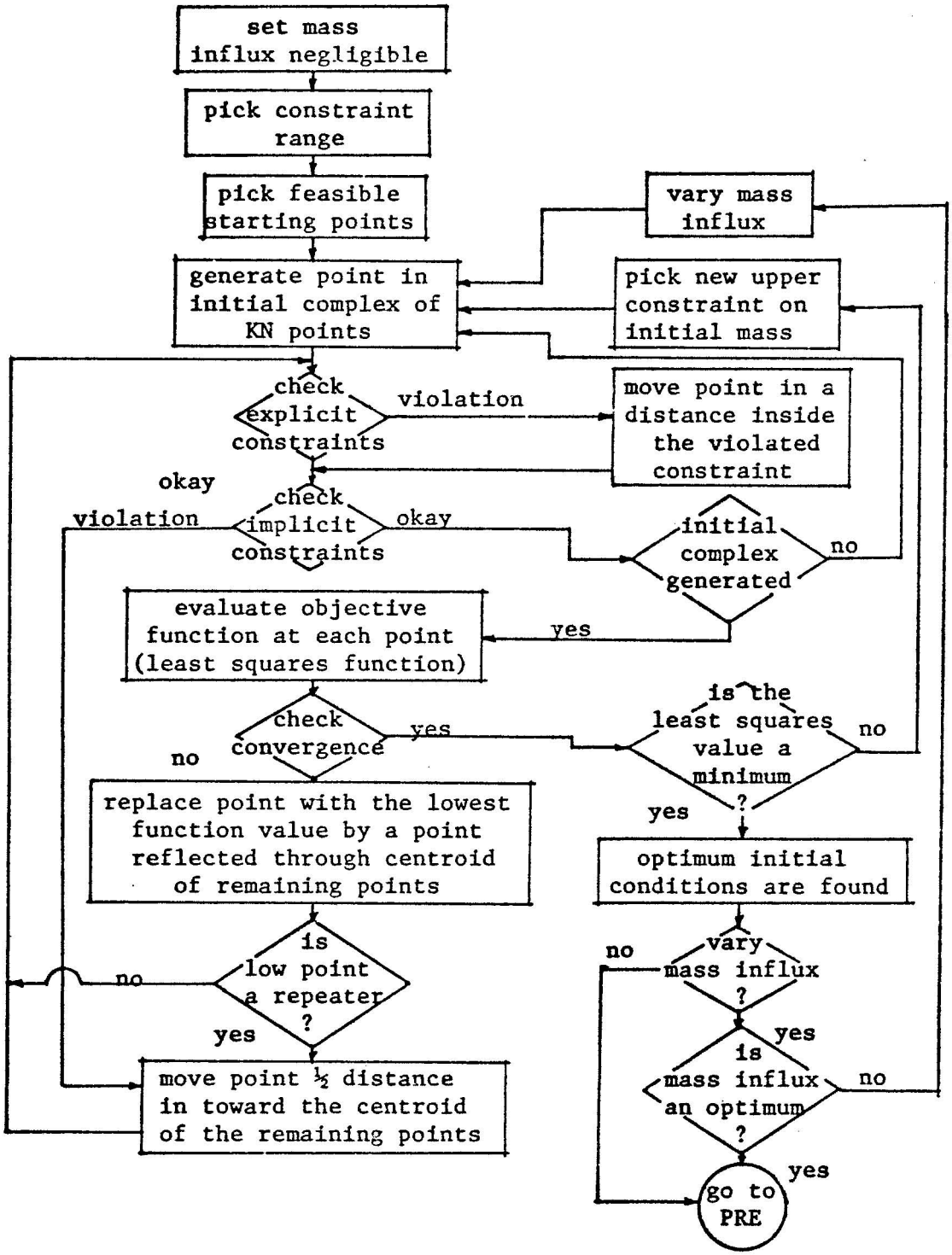


Figure 14. BOX Optimization Scheme (adapted from [25])

the geothermal reservoir. The three geothermal reservoirs considered are compressed liquid, saturated liquid-steam, and superheated steam. A flow chart of the general scheme is shown in Figure 15.

IV.2.2. Description of Computer Program PRE

This computer program is used to make a thirty-year projection of the performance for a geothermal reservoir, whether it be compressed liquid, saturated liquid-steam, or superheated steam. It can also be used to determine the effects of phase changes (e.g. the path from a single-phase region entering the two-phase region). The calculation scheme is as follows:

1. The optimum initial conditions determined from BOX are read into PRE.
2. These values are used in the material-energy balance equation to match the performance of the geothermal reservoir. If a phase change occurs during the performance matching, the user must remove the appropriate production data so the performance matching will end prior to the transition point, readjust the computer parameters, then start again.
3. Thirty-year projections are made at different production rates. In the event a phase change occurs during the predictions, the common boundary or transition point is determined. Once found, projections are continued until the thirty-year mark is reached, the reservoir pressure falls below 60 psia, or no current mass exists. In Figure 16 is displayed the general logic of program PRE.

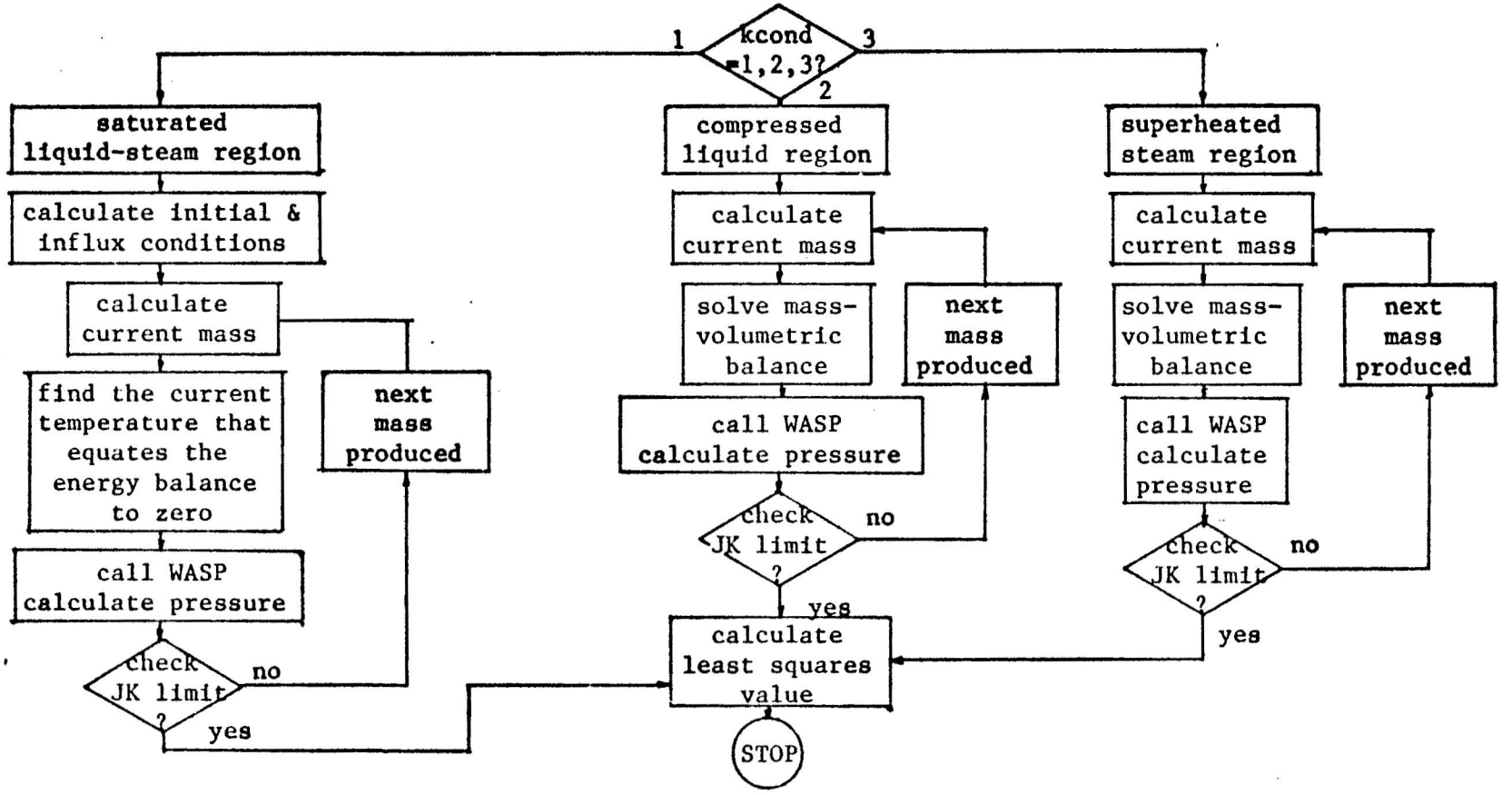


Figure 15. BOX - Subroutine FUNK Logic Diagram

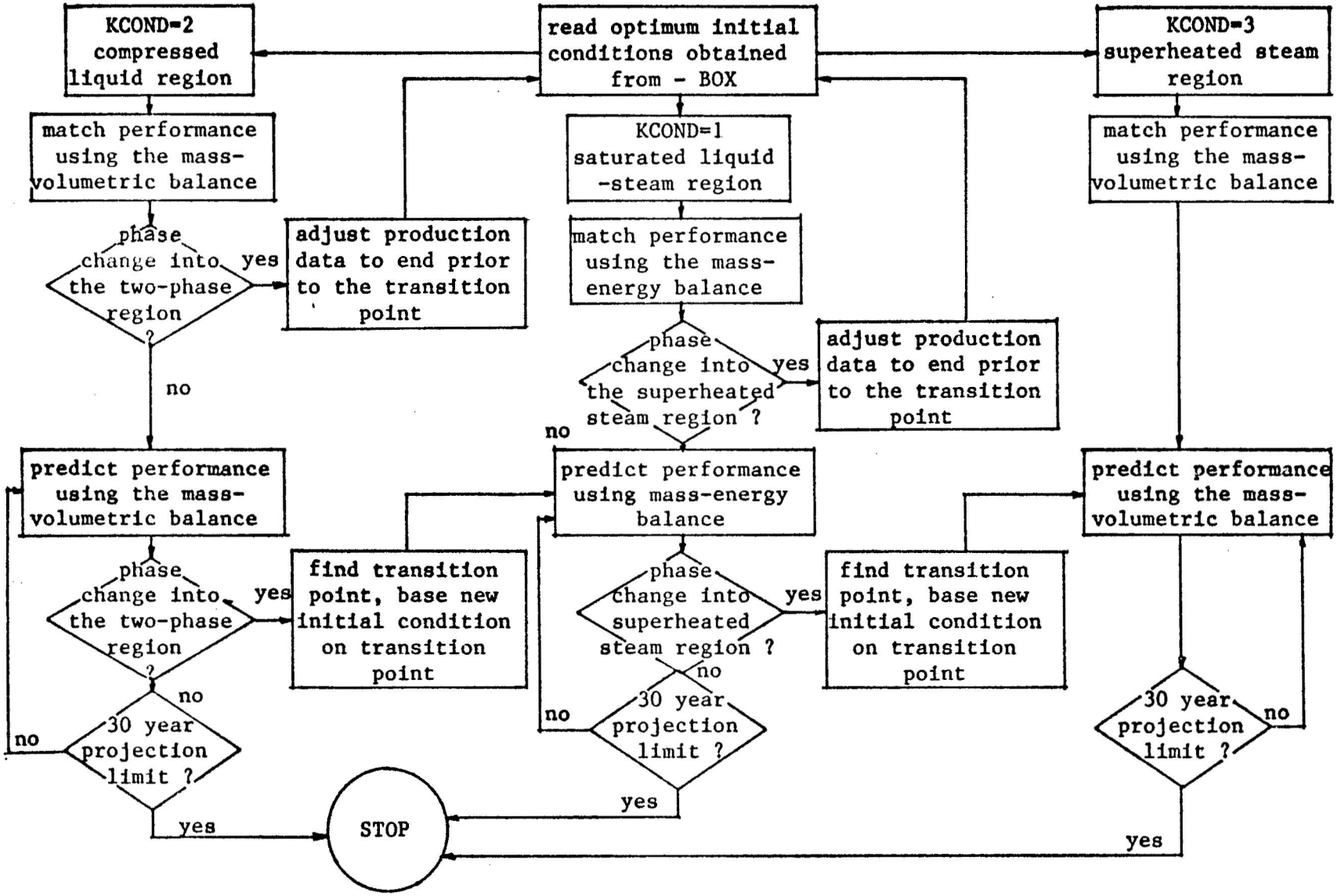


Figure 16. Computer Program PRE Logic Diagram

IV.2.3. Description of Subprogram WASP

WASP [26] is used to calculate the thermodynamic and transport properties of water and steam. It accepts any combination of pressure, temperature, or density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. The properties available in any combination as output include temperature, pressure, density, entropy, enthalpy, specific heats (C_p and C_v), sonic velocity, $(\partial P/\partial \rho)_T$, $(\partial P/\partial T)_\rho$, viscosity, thermal conductivity, surface tension, and the Laplace constant (WASP User's guide in Appendix F).

IV.3. Error Analysis

The convergence parameters of BOX are easily calculated (parameters defined in Appendix D). These values are multiples of either the function value or the independent variable values. Theoretically, a perfect fit will have a least squares value of zero. However, in the BOX program the calculated least squares value is truncated to an integer, so a zero least squares value will be a close, although not perfect fit.

To enable the use of WASP to calculate the thermodynamic properties of water and steam with a high degree of accuracy, the subprogram is operated in double precision. BOX and PRE, which make frequent calls to WASP, are also in double precision. In order to check for any discrepancies, the authors of WASP [26] made comparison plots of temperature, pressure, and density using the International Skeleton Tables for steam and water [27,28] as their references. Plots are in Appendix B.

Figure 34 represents the percent error in density as a function of density. With the exception of three points, all the values are within

+0.25 and -0.50 percent and generally have an error of less than 1 part in 3000. The error could be reduced by tightening the convergence criteria, however, this is not recommended because of the increased computer time and cost.

The relative error in pressure versus pressure is displayed in Figure 35. In all cases the calculated pressures are within +3.0 and -2.0 percent of the tabulated values. Most of the points lie within the $\pm$0.25 percent range. The prediction of pressure at high density (low temperature), using a fundamental equation or a state equation, is quite difficult, yet these errors are all within accepted tolerances.

The final comparison plot done with WASP (Figure 36) is the percent relative error of temperature versus temperature. With the exception of about a dozen points, the predicted temperatures are within +0.25 and -0.40 percent, lying generally in the $\pm$0.10 percent range.

Usually temperature and density are predictable because of the manner in which data was acquired, however, pressure is always difficult to calculate. With these basic guidelines in mind, a faithful representation of the International Skeleton Tables was made [26].

WASP appears in subroutine FUNK of both BOX and PRE quite frequently. In the two-phase section of each program, WASP was contained within a do-loop that conservatively made over 13,000 calls to WASP. This resulted in excessive computer time and extreme expense. To reduce the cost, general equations (36),(37),(38), and (39) (equations presented in Appendix G) for the desired thermodynamic properties were determined by linear regression. Keenan and Keyes' tabulated steam tables [29] was used as the reference for the chosen temperature range of 300°F to 600°F.

In Figure 37 is represented the percent relative error of enthalpy of saturated liquid (H_f) versus temperature. Except for five points at the temperature limits, the enthalpies are within $\pm$0.1 percent. Considering all the points, the range of +0.1 to -0.16 percent is still very good. The percent relative error of the enthalpy of saturated vapor (H_g) versus temperature was within $\pm$0.1 percent (Figure 38), while the specific volume of saturated liquid (V_f) versus temperature ranged from +0.3 to -0.2 percent (Figure 39).

The last thermodynamic property in question is the specific volume of saturated vapor (V_g) presented in Figure 40. The range of error was from +0.6 to -0.4 percent. The percent error is relatively high compared to the other three plots, but still within WASP's maximum relative error of 3.0 percent.

Re-examining Figures 37, 38, 39, and 40 it can be seen that the thermodynamic values at the upper extreme temperatures have the largest percent relative error. This was expected since temperature approaches the critical point (705.5 °F).

V. RESULTS AND DISCUSSION

This section is divided into three parts. The first part concerns the performance matching results, the second part concerns the results of the performance predictions, and the final part concerns the sensitivity analysis of the reservoir and BOX parameters.

Reservoir performance data to test each case was difficult to obtain because private firms generally treat reservoir data as proprietary. However, with assistance from Dr. James W. Mercer of the United States Geological Survey [30], five reels of microfilmed data from the Wairakei geothermal field was secured. A second set of production data was obtained with the help of Dr. R.S. Bolton [31], chief geothermal engineer with the Ministry of Works and Development in New Zealand [32]. The third and final set of production data was found in a publication by Henry J. Ramey Jr. [23].

V.1. Performance Matching

In Table 3 is displayed the optimum initial conditions and minimum least squares value for the three geothermal reservoirs studied:compressed liquid, saturated liquid-steam, and superheated steam. Negligible mass influx and a large mass influx (determination of mass influx rate in V.3. Sensitivity Analysis) were two cases studied for each reservoir. The influx temperature was kept at 960°R throughout the entire matching analysis. For the reservoirs studied it appeared that large mass influx gave better curve fits. This was especially true for the compressed liquid case, in which the least squares value decreased from

Table 3. Optimum Initial Parameters of a Geothermal Reservoir

Reservoir Parameter	Without Mass Influx	With Mass Influx
Compressed Liquid:		
Initial Pressure	772.38813	773.879926
Initial Mass	$5.41981569 \times 10^{14}$	$4.87952480 \times 10^{14}$
Least Squares Value	105	80
Saturated Liquid-Steam:		
Initial Temperature	952.518912	952.739672
Initial Mass	$1.87592409 \times 10^{12}$	$1.77168640 \times 10^{12}$
Initial Steam Quality	0.078475	0.014552
Least Squares Value	8	4
Superheated Steam:		
Initial (Pressure/Compressibility Factor)	188.162590	191.32409
Initial Mass	2.3119401×10^{11}	1.8274845×10^{11}
Least Squares Value	0	0

105 to 80. The saturated liquid-steam case, which already had a good fit of 8, had a fit of 4 with a large mass influx, while the superheated steam case had a nearly perfect fit in both influx situations.

In Tables 4 and 5 are shown the compressed liquid reservoir conditions for BOX and the production data used, respectively. In Figure 17 is displayed the performance matching of a compressed liquid reservoir with negligible mass influx. The least squares value of 105 is rather large in comparison with the other geothermal reservoirs matched, but is, in effect, the best fit for the given production data. A performance match of a compressed liquid with a large mass influx rate of 1.0×10^{10} lb/yr is shown in Figure 18. A close inspection of Figures 17 and 18 will show a slight variation between the two matches.

Table 4. Compressed Liquid Reservoir Conditions for BOX

initial parameter	starting value	lower constraint	upper constraint
pressure, psia	750.0	724.7	800.0
mass, lb	1.0×10^{15}	1.0×10^{13}	1.0×10^{17}

Whiting [33] tested the model on Wairakei data. He assumed negligible mass influx, mass loss, and heat loss. Table 6 shows the results of Whiting-Ramey model in comparison with the HGP model. The values are essentially in agreement with each other.

Table 5. Compressed Liquid Reservoir Production Data

average reservoir pressure, psia	cumulative mass produced, lb
724.7	1.98080×10^{11}
719.7	2.63323×10^{11}
708.7	3.34383×10^{11}
685.7	4.47215×10^{11}
651.7	5.82333×10^{11}
625.7	7.03257×10^{11}

$W_L = 1.0$ lb/yr

$T_i = T_c = 924$ °R

Table 6. Comparison of Results for a Compressed Liquid Reservoir

initial parameter	Whiting-Ramey Model	HGP Model
pressure, psia	773.3	772.38813
mass, lb	5.234×10^{14}	5.4198×10^{14}

$W_L = W_e = Q_s = 0.0$

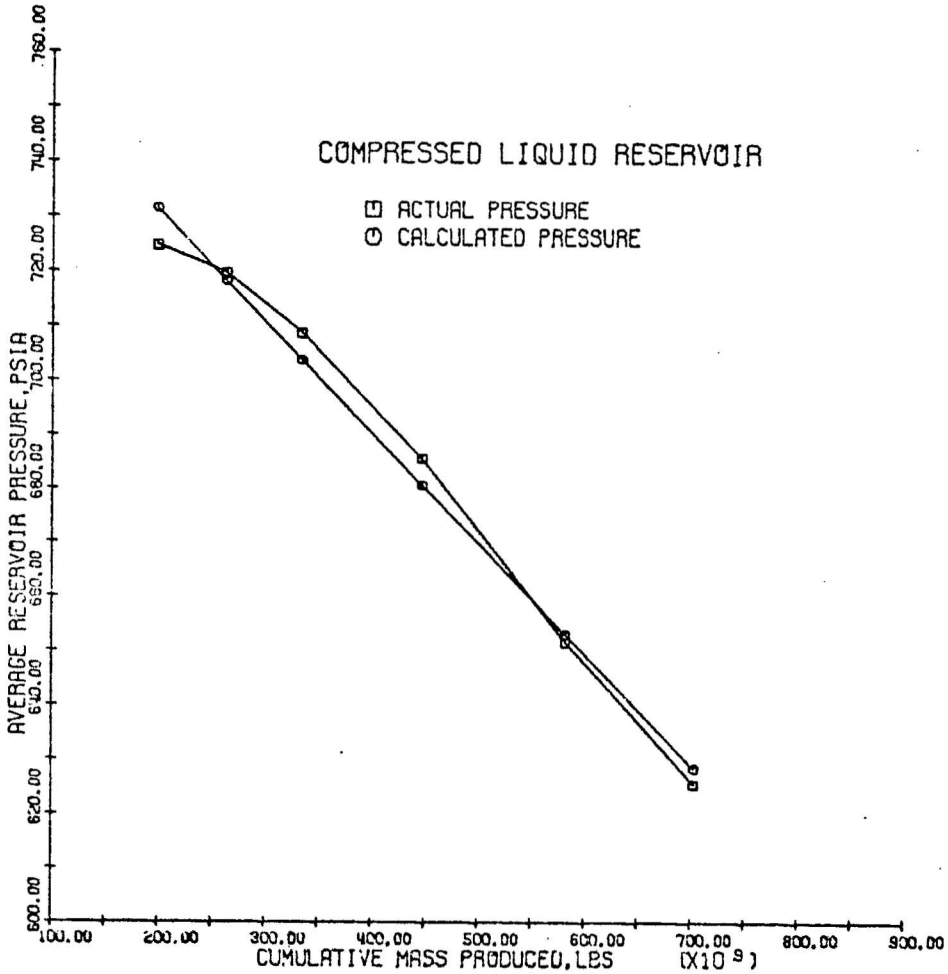


Figure 17. Performance Matching with the Mass Influx Rate = 1.0 lb/yr

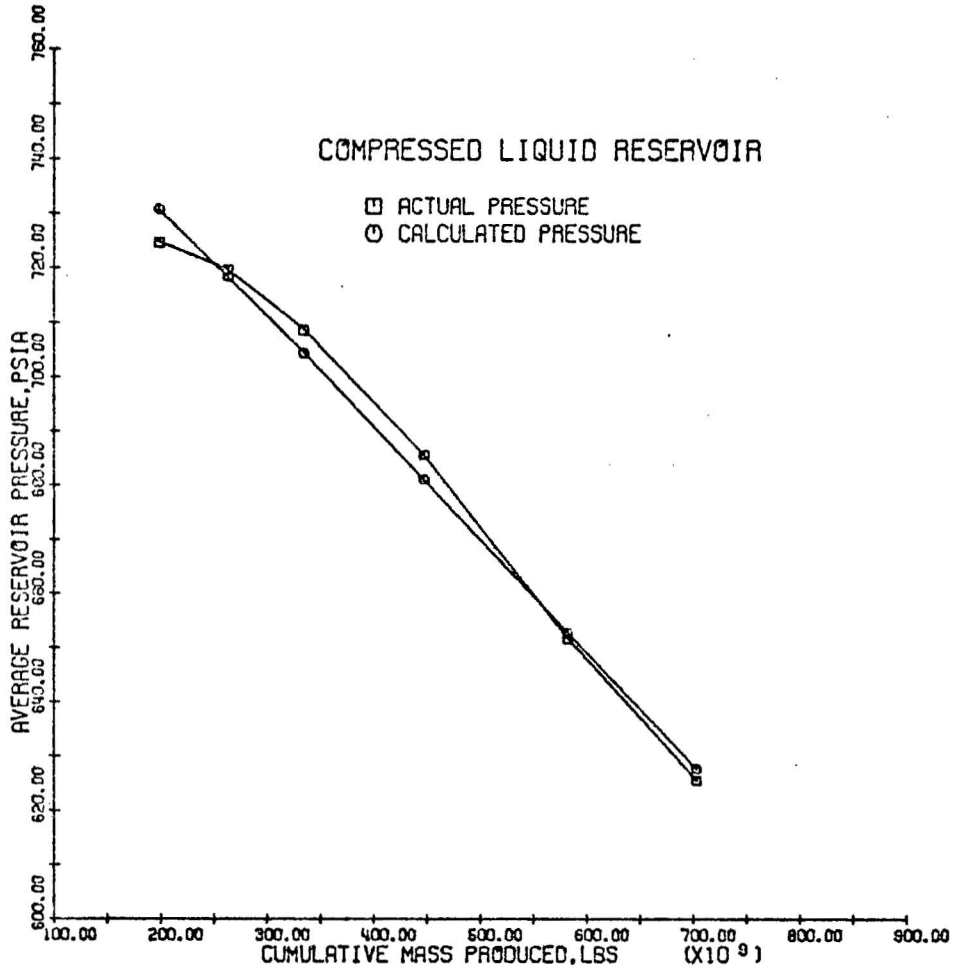


Figure 19 Performance Matching with the Mass Influx Rate = 1.0 X 10^{10} lb/yr

In Tables 7 and 8 are the saturated liquid-steam reservoir conditions for BOX and the production data used, respectively. With the given performance data, the best curve fit obtainable is shown in Figure 19. The least squares value was 8 in the case of negligible mass influx, but with a mass influx of 1.0×10^{10} lb/yr (starting at 2.0×10^{10} lb) the curve fit value was 4 (Figure 20). In this case, the difference in the curve fits is easily detected.

Table 7. Saturated Liquid-Steam Reservoir Conditions for BOX

initial parameter	starting value	lower constraint	upper constraint
temperature, °R	930.0	800.0	1000.0
mass, lb	1.0×10^{13}	1.5×10^{12}	7.5×10^{12}
steam quality	0.1	0.0	1.0

Table 8. Saturated Liquid-Steam Reservoir Production Data

average reservoir pressure, psia	cumulative mass produced, lb
618.0	1.0180×10^{12}
608.0	1.1600×10^{12}
597.0	1.2910×10^{12}
587.0	1.4030×10^{12}

W_L = 1.0 lb/yr
Q_s^L = 1.0 lb/yr
rock density = 190 lb/ft^3
porosity = 0.2
influx temperature = 960 °R

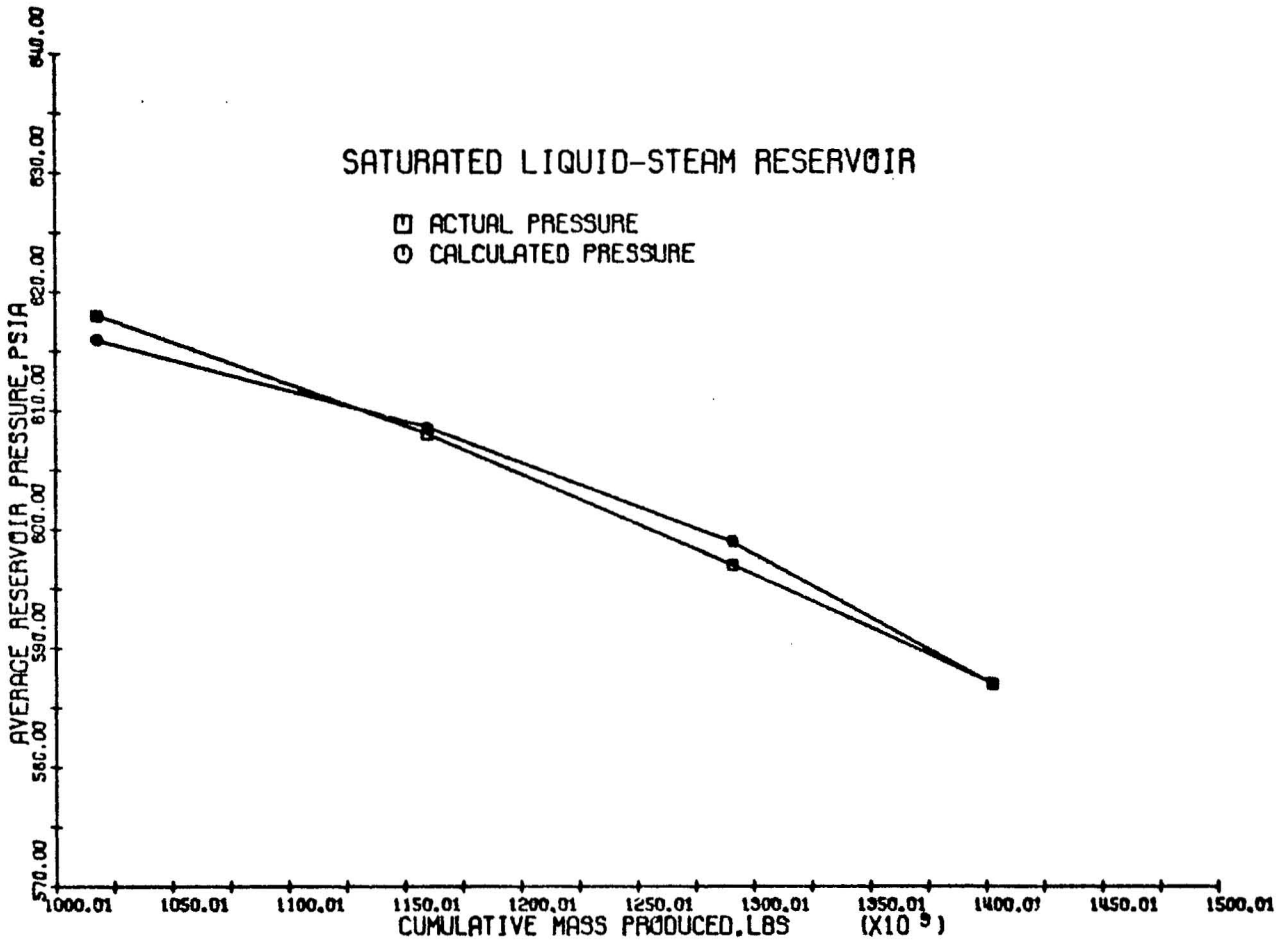


Figure 19. Performance Matching with the Mass Influx Rate = 1.0 lb/yr

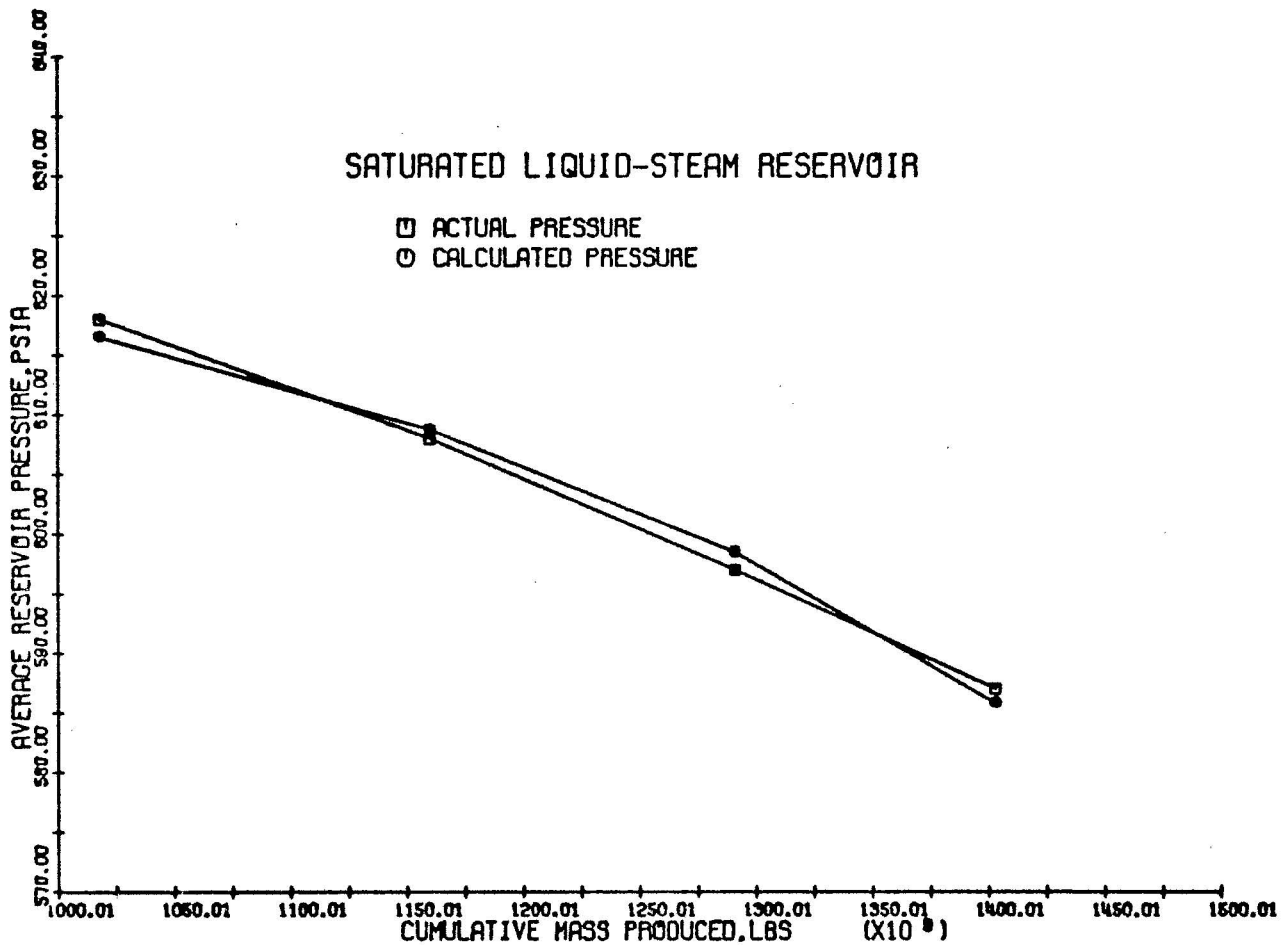


Figure 20. Performance Matching with the Mass Influx Rate = 1.0 X 10^{10} lb/yr (Starting at 2.0 X 10^{10} lb)

The third match is of the superheated steam reservoir. In Tables 9 and 10 are displayed the BOX conditions and production data used, respectively. As mentioned before, a zero least squares value is theoretically a perfect fit;however, BOX truncates the value to an integer, so the least squares value is not the true value. The curves in Figures 21 and 22 both have least squares values of zero for the condition of negligible mass influx and a mass influx rate of 1.0×10^9 lb/yr, respectively. The effect of a large mass influx is detectable when the two curve fit plots are compared.

Table 9. Superheated Steam Reservoir Conditions for BOX

initial parameter	starting value	lower constraint	upper constraint
P_i/Z_i, psia	190.0	165.0	225.0
mass, lb	1.0×10^{11}	5.0×10^{10}	5.0×10^{11}

Table 10. Superheated Steam Reservoir Production Data

average reservoir pressure, psia	cumulative mass produced, lb
164.0	1.6706×10^{10}
160.0	2.1083×10^{10}
156.0	2.6382×10^{10}
152.0	3.2580×10^{10}
148.0	3.8090×10^{10}
145.0	4.3032×10^{10}
142.0	4.7000×10^{10}
$W_L = 1.0$ lb/yr	$T_i = T_c = 860°R$

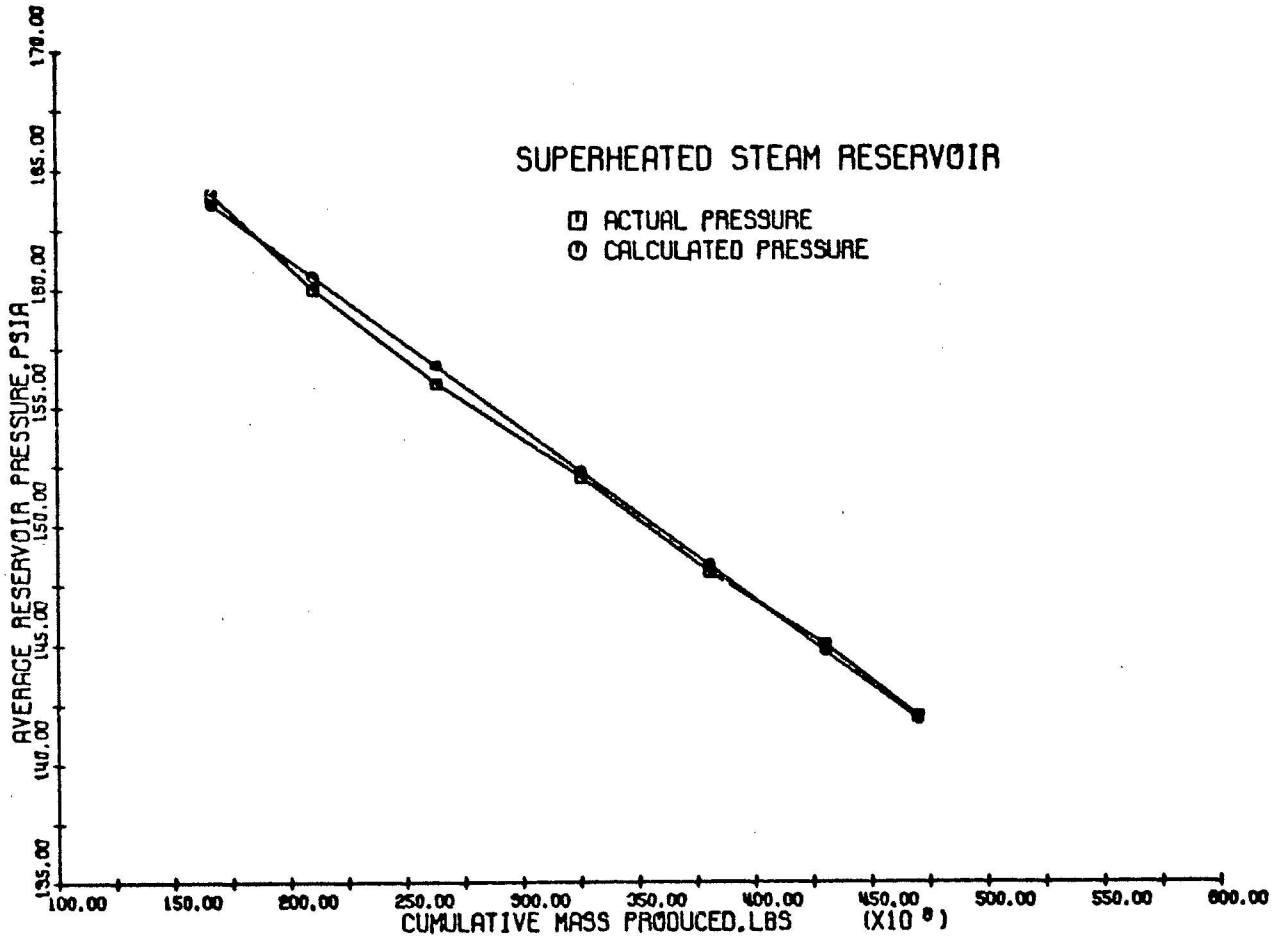


Figure 21. Performance Matching with the Mass Influx Rate = 1.0 lb/yr

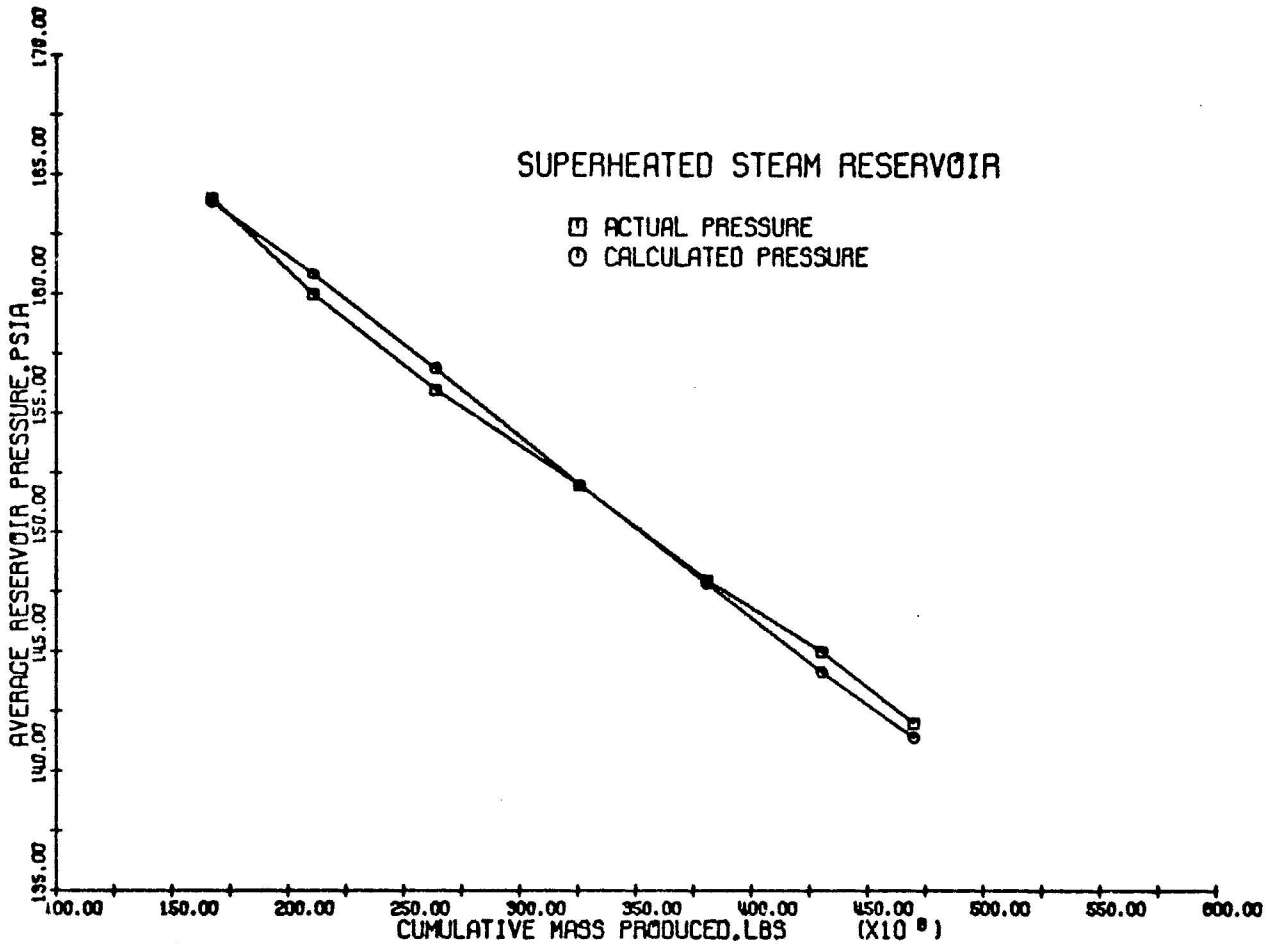


Figure 22. Performance Matching with the Mass Influx Rate = 1.0 X 10^9 lb/yr

Henry J. Ramey Jr. [23] reported that the usual gas reservoir engineering manner for predictions is made by extrapolating P/Z versus cumulative production plot. Other information such as the initial conditions can also be obtained from this plot. In Table 11 are his estimates from the plot in comparison with the values obtained from the HGP model. The results are in relative agreement with each other.

Table 11. Comparison of Results for a Superheated Steam Reservoir

initial parameter	Ramey's Plot	HGP Model
P_i/Z_i, psia	190.0	188.16259
mass, lb	2.15×10^{11}	2.3119×10^{11}

$W_e = W_L = 0.0$

V.2. Performance Prediction

The optimum initial conditions obtained from BOX (Table 3) are read into PRE for the predictions of future performance. A thirty-year projection was made using 60 psia as the abandonment pressure and 960°R as the influx temperature.

In Figure 23 is shown the perfomance prediction of a compressed liquid reservoir with negligible mass influx at seven different production rates. The two lower rates reveal a small pressure drop. The production rate of 1.0×10^{10} lb/yr has an apparent pressure drop as mass is being produced. At a pressure of 487.16 psia, a phase change from the compressed liquid region to the saturated liquid-steam region occurs. The two-phase region is reached earlier in the predictions at

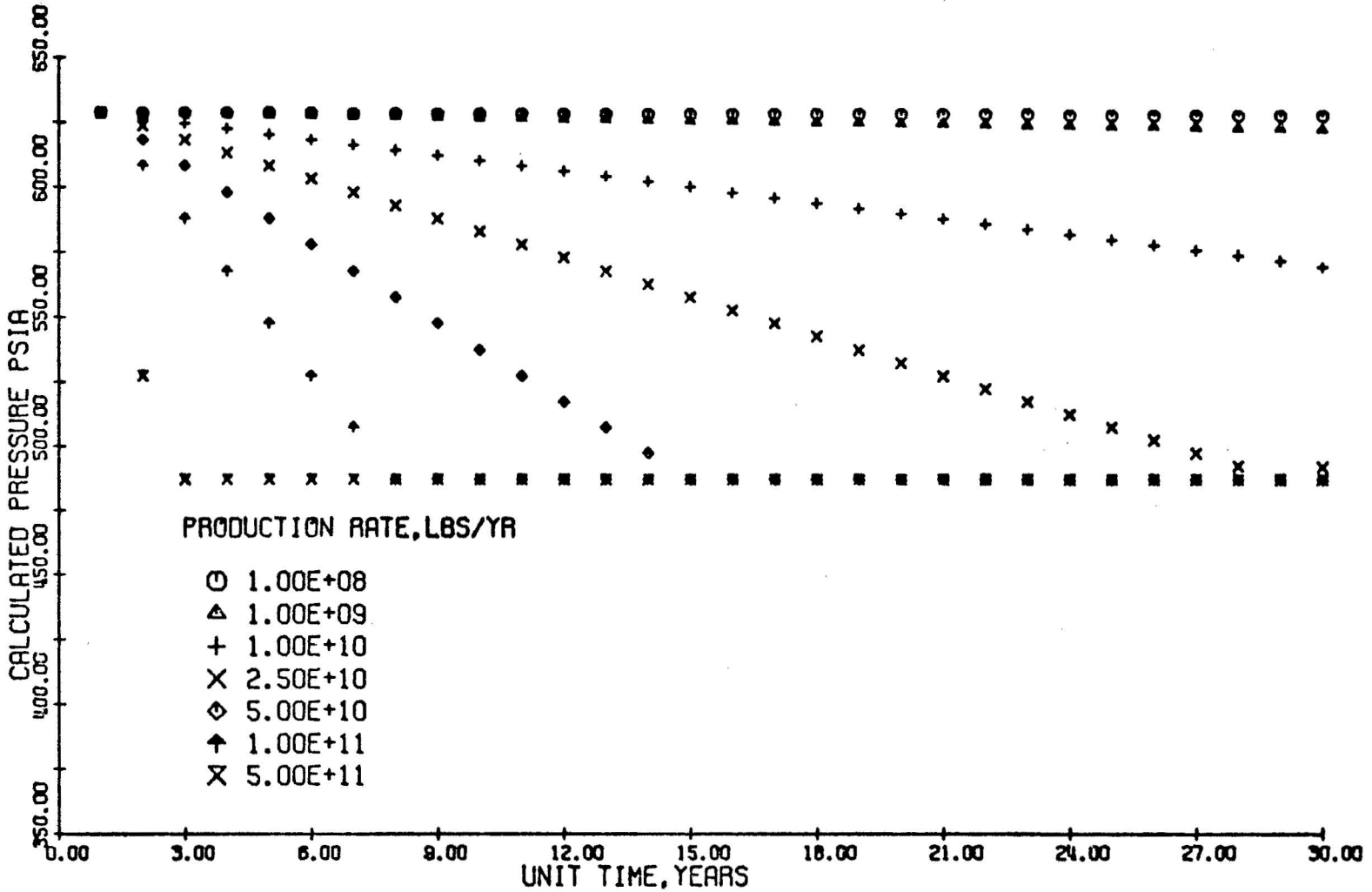


Figure 23. Performance Prediction of a Compressed Liquid Reservoir with the Mass Influx Rate = 1.0 lb/yr

the higher production rates. Figure 24 is a plot of predictions for a compressed liquid reservoir with a mass influx rate of 1.0×10^{10} lb/yr. The pressure increase at the lower two production rates was expected because the mass influx is much greater than the mass produced. Since isothermal conditions prevail, the large mass influx effects can only result in a pressure rise. When the production and mass influx rates are equal the pressure remains constant. The mass influx effects are displayed graphically by a slight counterclockwise rotation of each prediction curve. Physically, the reservoir will have a longer life expectancy. The phase change still occurs at the same pressure, 487.16 psia.

The predictions for a saturated liquid-steam reservoir with negligible mass influx are illustrated in Figure 25. Again the two lower production rates show no decrease in reservoir pressure. At the production rates of 1.25×10^{10} lb/yr and larger, a phase change from the saturated liquid-steam region to the superheated steam region occurs. This is displayed by the sudden change in slope of the prediction curve. Once in the superheated steam region, the reservoir depletes rapidly. The predictions for a saturated liquid-steam reservoir with a mass influx rate of 1.0×10^{10} lb/yr (starting at 2.0×10^{10}) are shown in Figure 26. The increase in pressure at the two lower production rates was anticipated. Since the heat influx is greater than the amount of heat produced, the effect is an increase in reservoir temperature. In the saturated liquid-steam case, pressure is a function of temperature, therefore pressure also increases. At the 1.25×10^{10} lb/yr production rate, the phase change does not occur within the thirty-year prediction.

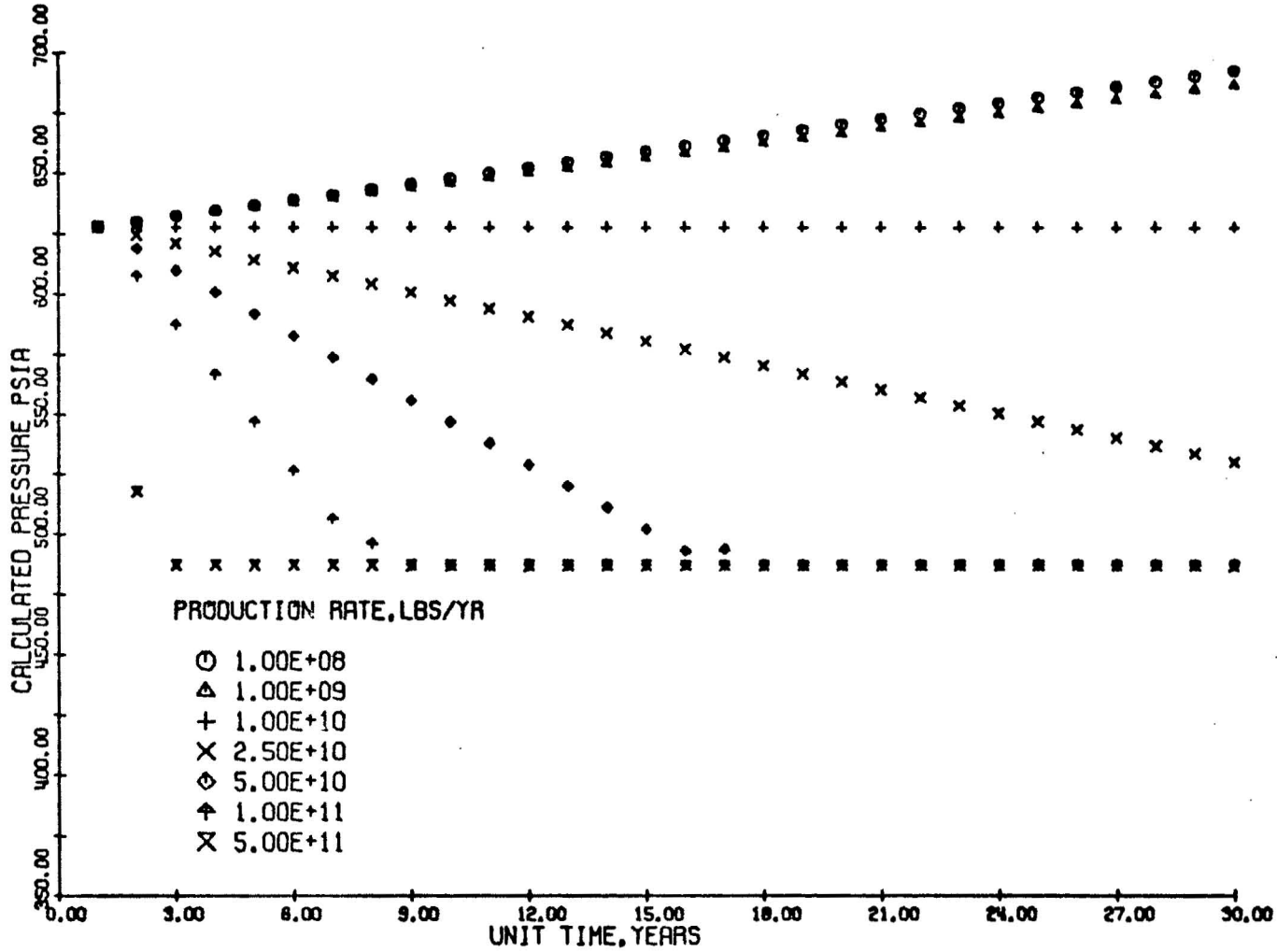


Figure 24. Performance Prediction of a Compressed Liquid Reservoir with the Mass Influx Rate = 1.0 X 10^{10} lb/yr

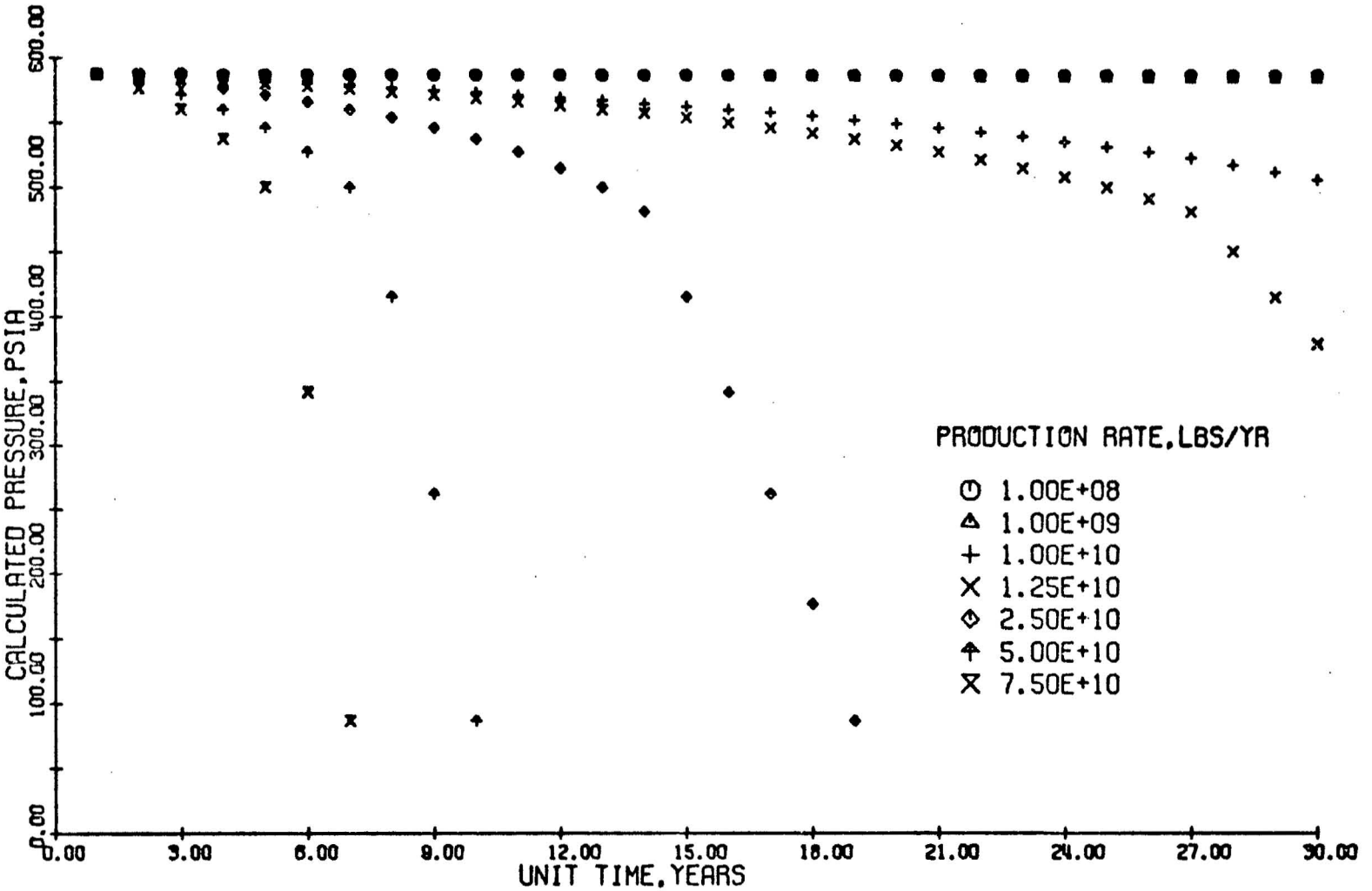


Figure 25. Performance Prediction of a Saturated Liquid-Steam Reservoir with the Mass Influx Rate = 1.0 lb/yr

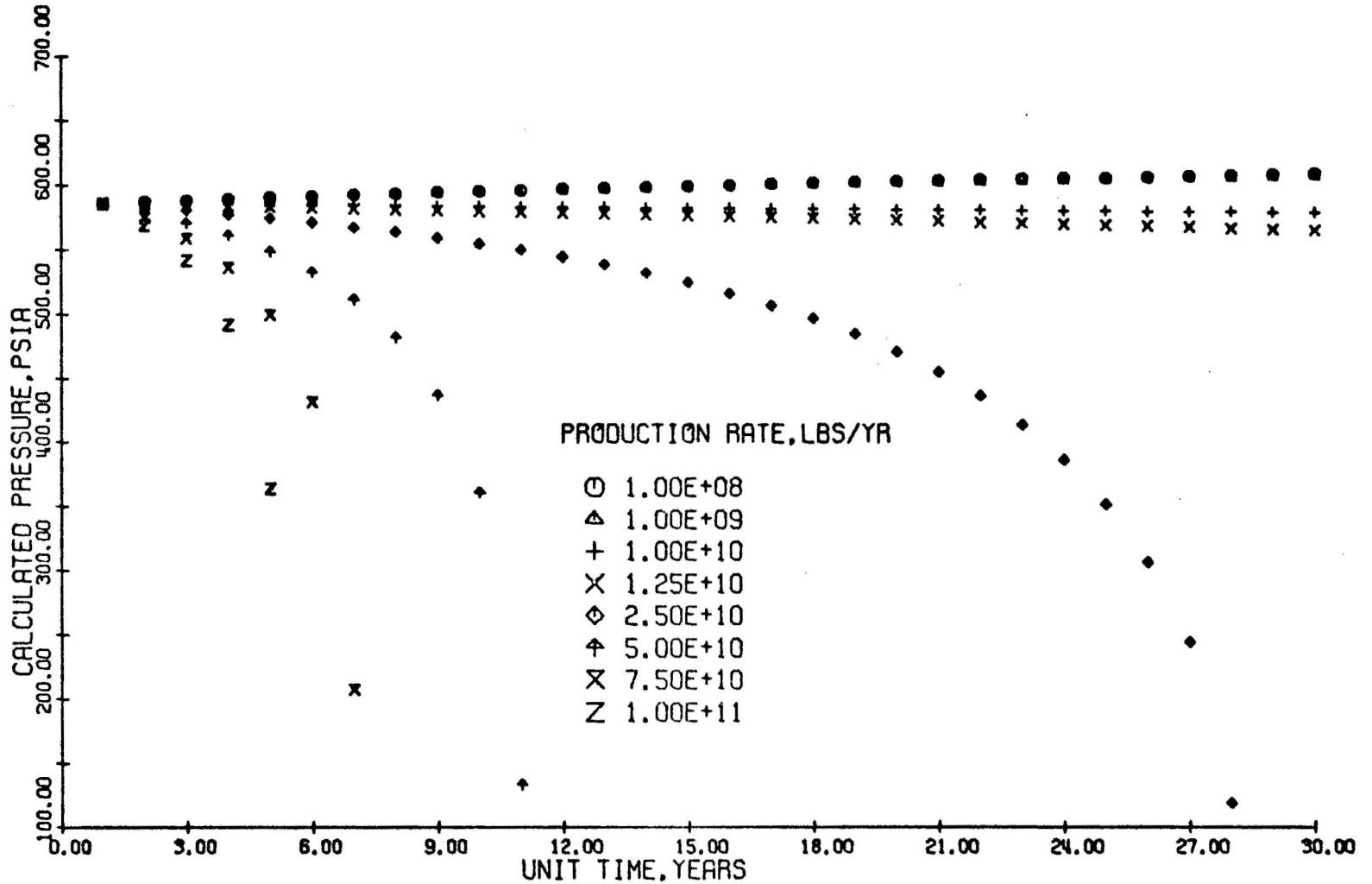


Figure 26. Performance Prediction of a Saturated Liquid-Steam Reservoir with the Mass Influx Rate = 1.0 X 10^{10} lb/yr (Starting at 2.0 X 10^{10} lb)

Large mass influx affects the predictions graphically by rotating the curves about the "year one" point. Physically, the reservoir will have a slightly longer production life.

The final performance prediction was done on a superheated steam reservoir. In Figure 27 is presented the prediction curves with insignificant mass influx;in Figure 28 is displayed the prediction plots with a mass influx rate of 1.0×10^9 lb/yr. The reasons for increasing pressures at the low production rates in the superheated steam case are similar to those for the compressed liquid case. Large mass influx is greater than the mass being produced, therefore the reservoir pressure will rise (isothermal conditions exist) because of the higher heat input. The effects of a large mass influx gave the reservoir a slightly longer production life before it reached the abandonment pressure.

In general, a large mass influx rate will have a positive effect on a geothermal reservoir performance prediction curve. The geothermal reservoir can expect to have a longer life expectancy. The pressure increase in the geothermal reservoir at the low production rates may be realistic at the start of production, but in actuality would certainly not continue throughout the reservoir's production life.

V.3. Sensitivity Analysis

The parameters examined in the sensitivity analysis are the reservoir properties of the saturated liquid-steam case and the mass influx rate for all the reservoirs. The upper and lower constraints for each initial parameter of BOX were also checked. As mentioned before, the chances of finding the optimum initial conditions are highly dependent

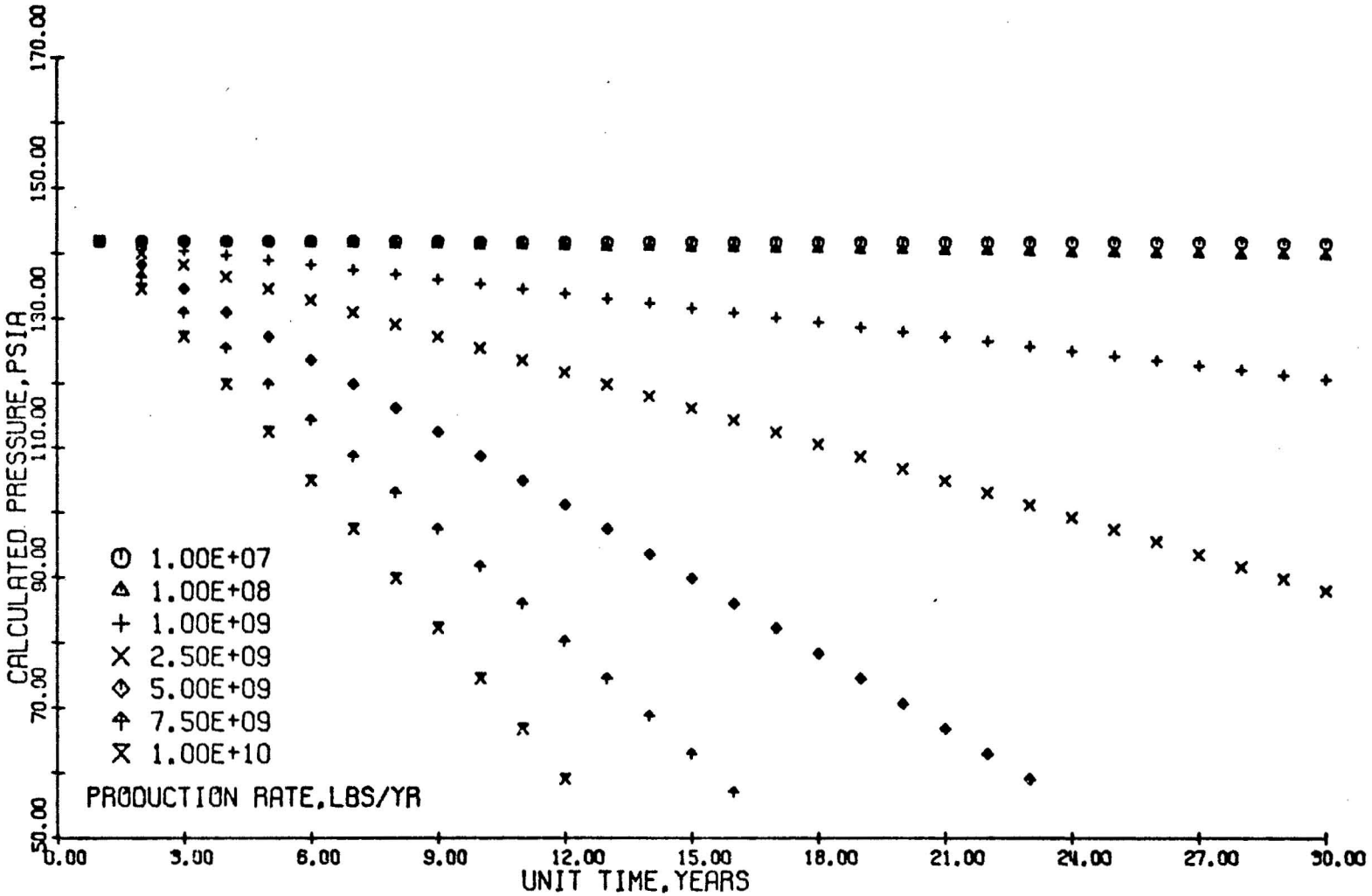


Figure 27. Performance Prediction of a Superheated Steam Reservoir with the Mass Influx Rate = 1.0 lb/yr

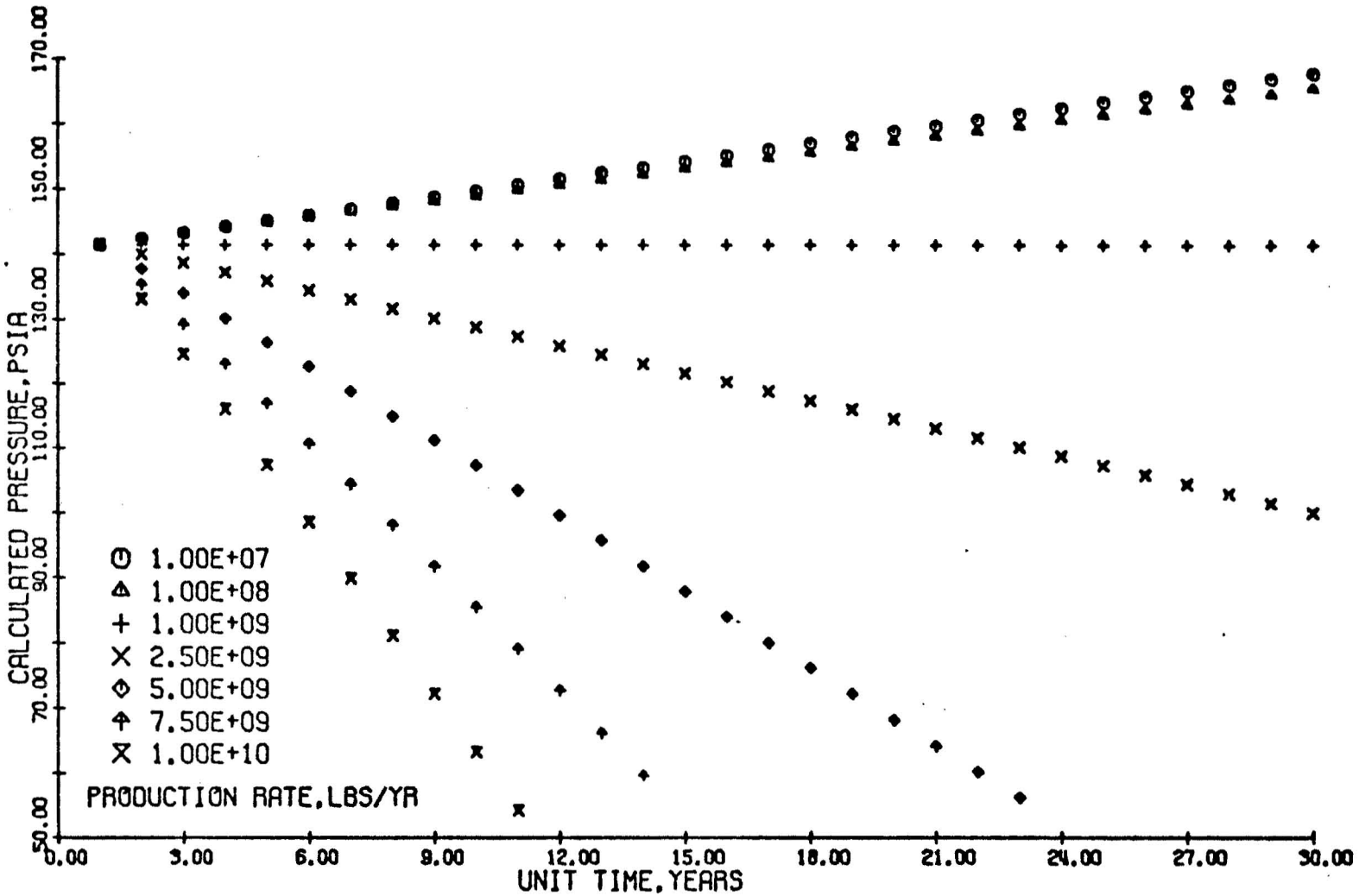


Figure 28. Performance Prediction of a Superheated Steam Reservoir with a Mass Influx Rate = 1.0 X 10^9 lb/yr

on the constraints chosen for each parameter.

In the sensitivity analysis, only the designated parameter was varied, while the others were kept constant. The mass influx was assumed to be negligible unless specified as the parameter under investigation. The parameter values of BOX used were presented in Tables 4, 7, and 9. The term "confidence range" will be applied quite frequently. This term is defined as the maximum allowable range of the upper or lower constraint value that the user will have to obtain a good least squares fit. Mass lost, W_L, and heat influx, Q_s, were ignored in this study, because the sensitivity analysis of mass influx, W_e, and influx temperature, T_e, in effect include these terms in the analysis. The tables of the sensitivity analysis data are presented in Appendix C.

V.3.1. Compressed Liquid Reservoir

In Table 12 is presented the variations of the upper and lower constraints of initial pressure. The upper constraint has a wide confidence range of values from 775.0 psia to 1000.0 psia, however, at 875.0 psia, the least squares value deviated to 122, while the rest of the values remained at 105. This variation can be attributed to the search technique of BOX. Figure 29 is a contour plot of the least squares equation as a function of initial pressure and initial mass. It is highly possible that the search path iterated about a narrow ridge, as at the 120 mark, or it may have found a local minimum not shown in the plot. The lower constraint also had a wide confidence range. The values, which had good fits, were from 710.0 psia to 750.0 psia.

In Table 13 is shown the initial mass variations. The upper con-

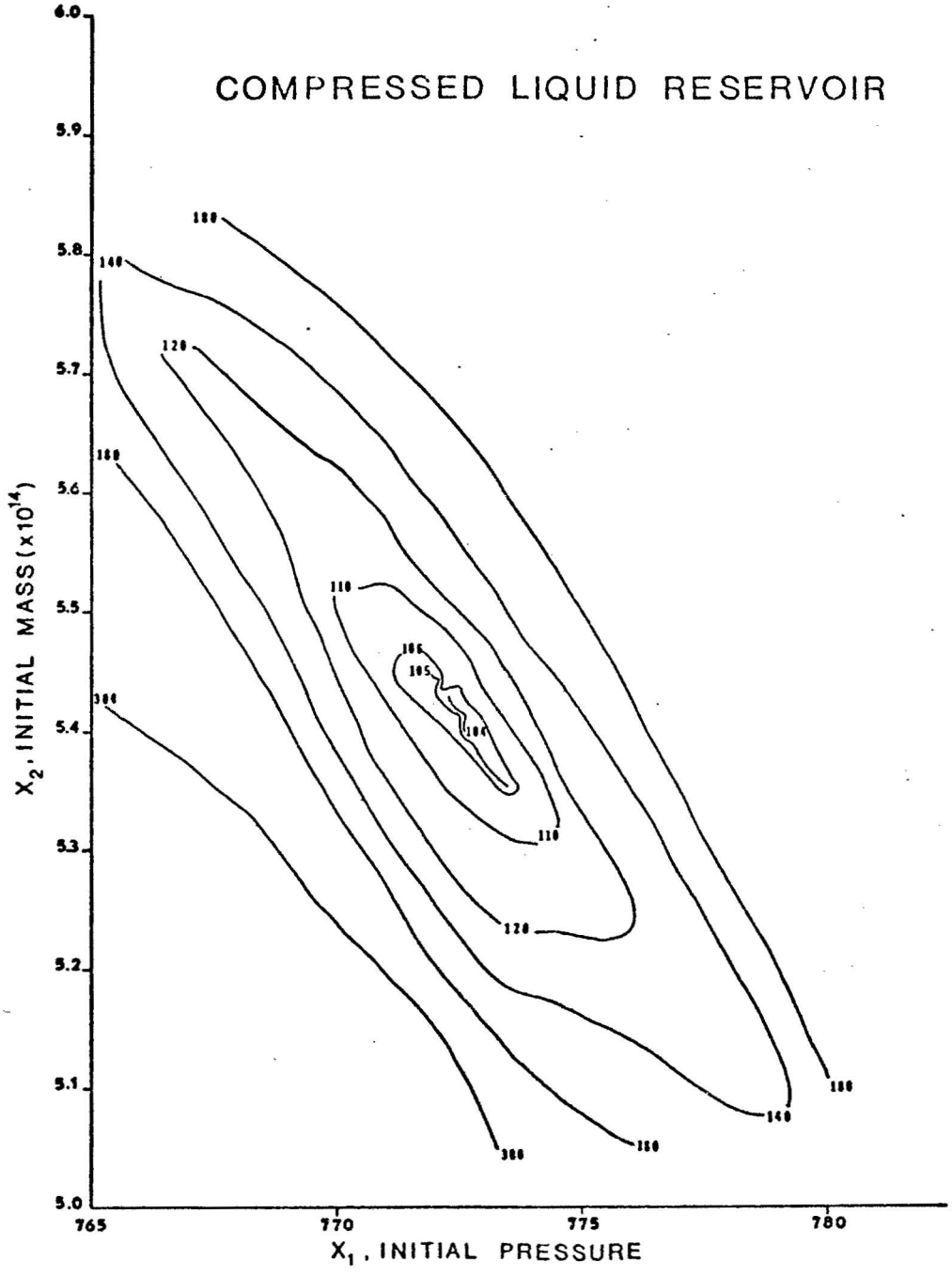


Figure 29. Contour Plot of Least Squares Function

straint has a wide confidence range from 1.0 X 10^{15} lb to 1.0 10^{17} lb. The lower constraint has a good curve fit from 1.0 X 10^{12} lb X 10^{14} lb.

In Table 14 is displayed the effect of mass influx on the curve fitting. The mass influx rate of 7.0 X 10^{10} lb/yr was the maximum allowable influx that yielded a good least squares fit. All mass influx rates that were larger than 7.0 X 10^{10} lb/yr had relatively high curve fit values (invalid curve fits). However, at 1.0 X 10^{10} lb/yr, the least squares value was the lowest at 80. This rate was used in performance matching and predictions presented earlier.

V.3.2. Saturated Liquid-Steam Reservoir

The saturated liquid-steam results of changes to the upper and lower constraints of the initial temperature are displayed in Table 15. The confidence range is quite small for the upper constraint (990.0°R to 1000.0°R). The lower constraint also has a narrow confidence range from 780.0°R to 800.0°R.

In Table 16 is presented a very small confidence range on the upper constraint of initial mass (7.49 X 10^{12} lb to 7.50 X 10^{12} lb). The lower constraint has two isolated values which produce low curve fit values. This low-high-low effect of the least squares values could best be explained by examining contour plots of the least squares function (Figures 30, 31, and 32). In this case, the plot is not two-dimensional, but three-dimensional, because of the three unknown initial parameters. The contour plots are represented at initial steam quality values of 0.0, 0.07847, and 1.0, respectively. Though the contour field is difficult to visualize, it is believed that the search technique of BOX is

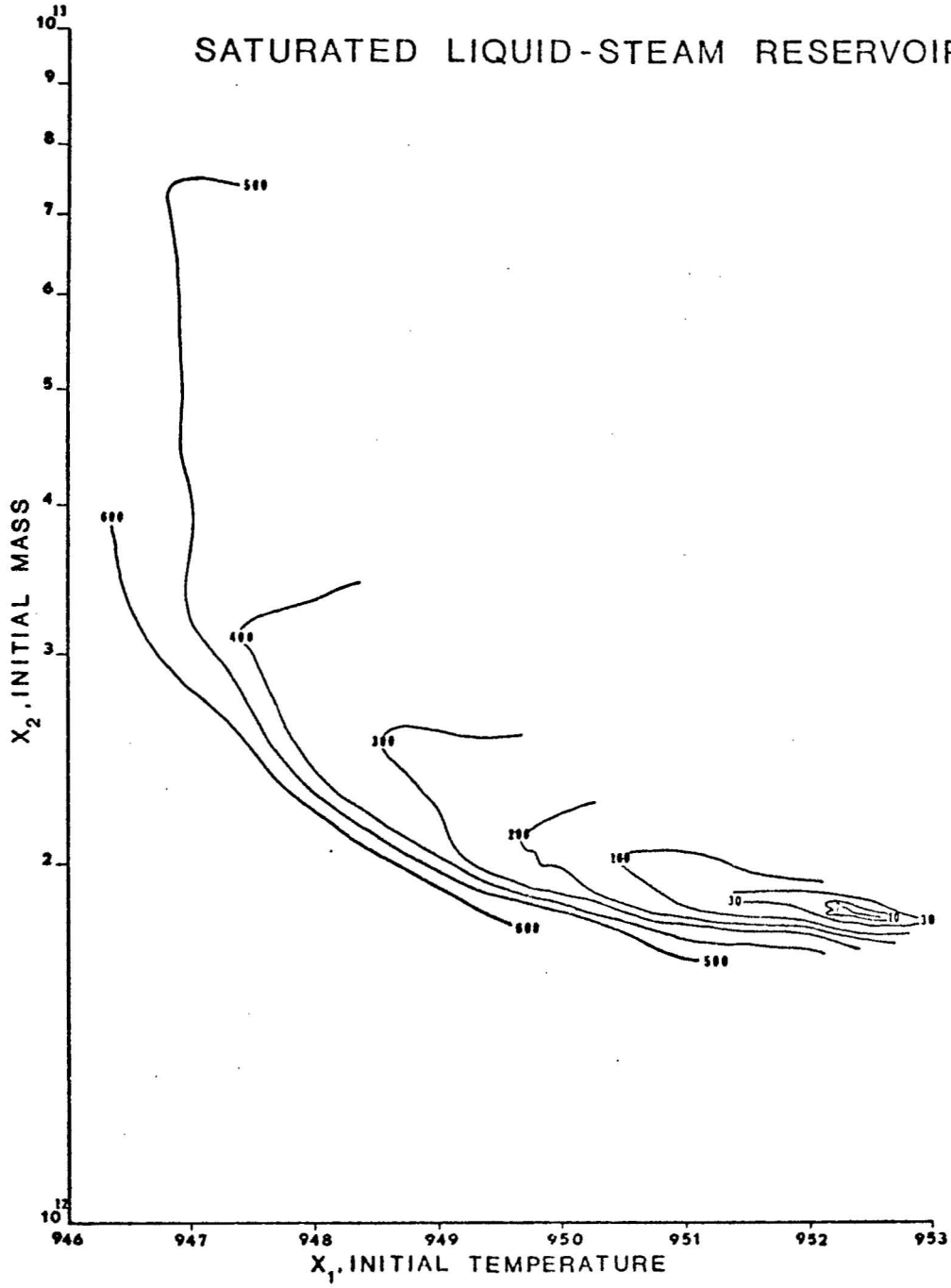


Figure 30. Contour Plot of Least Squares Function with Initial Steam Quality = 0.0

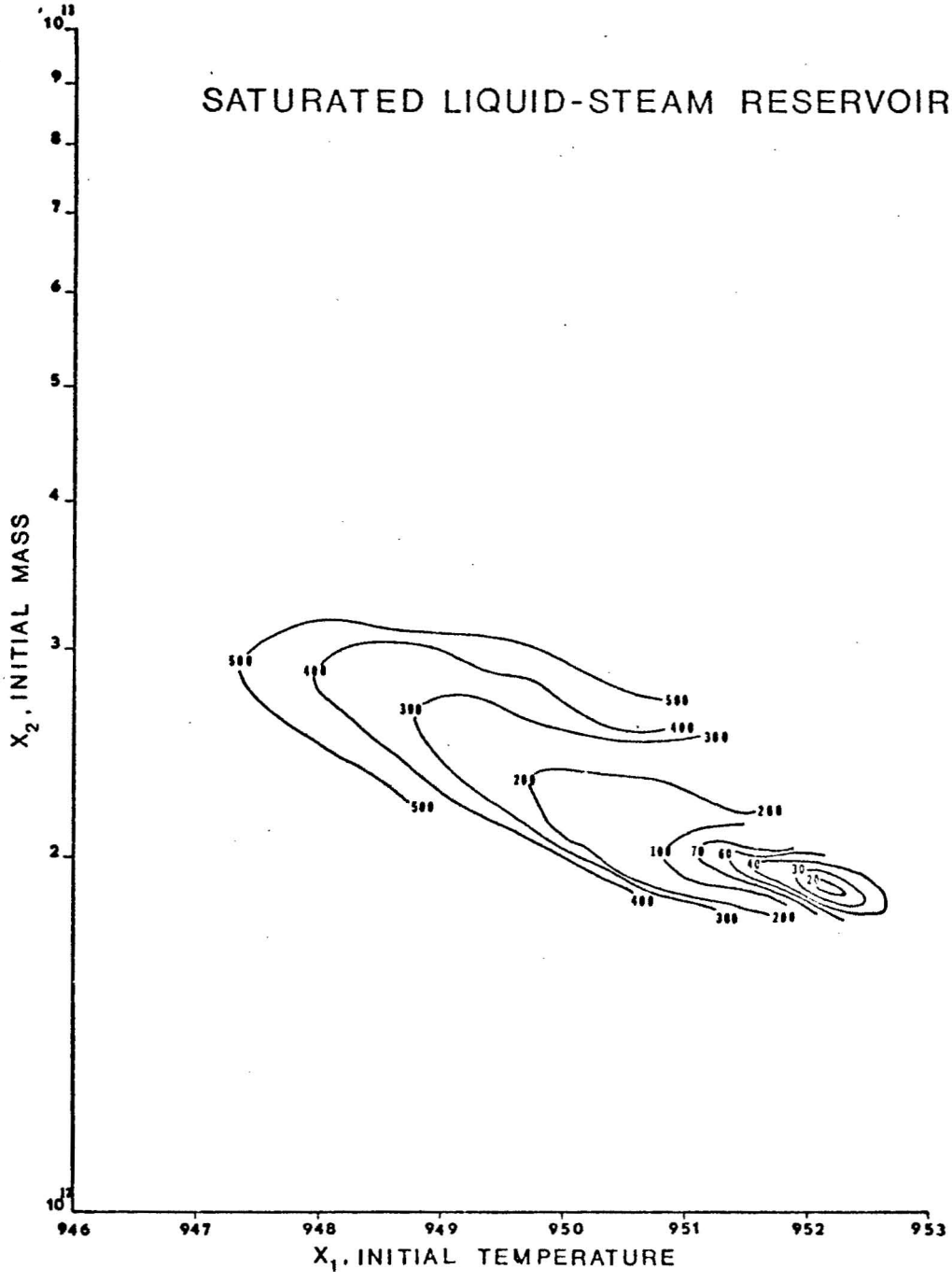


Figure 31. Contour Plot of Least Squares Function with Initial Steam Quality = 0.07847

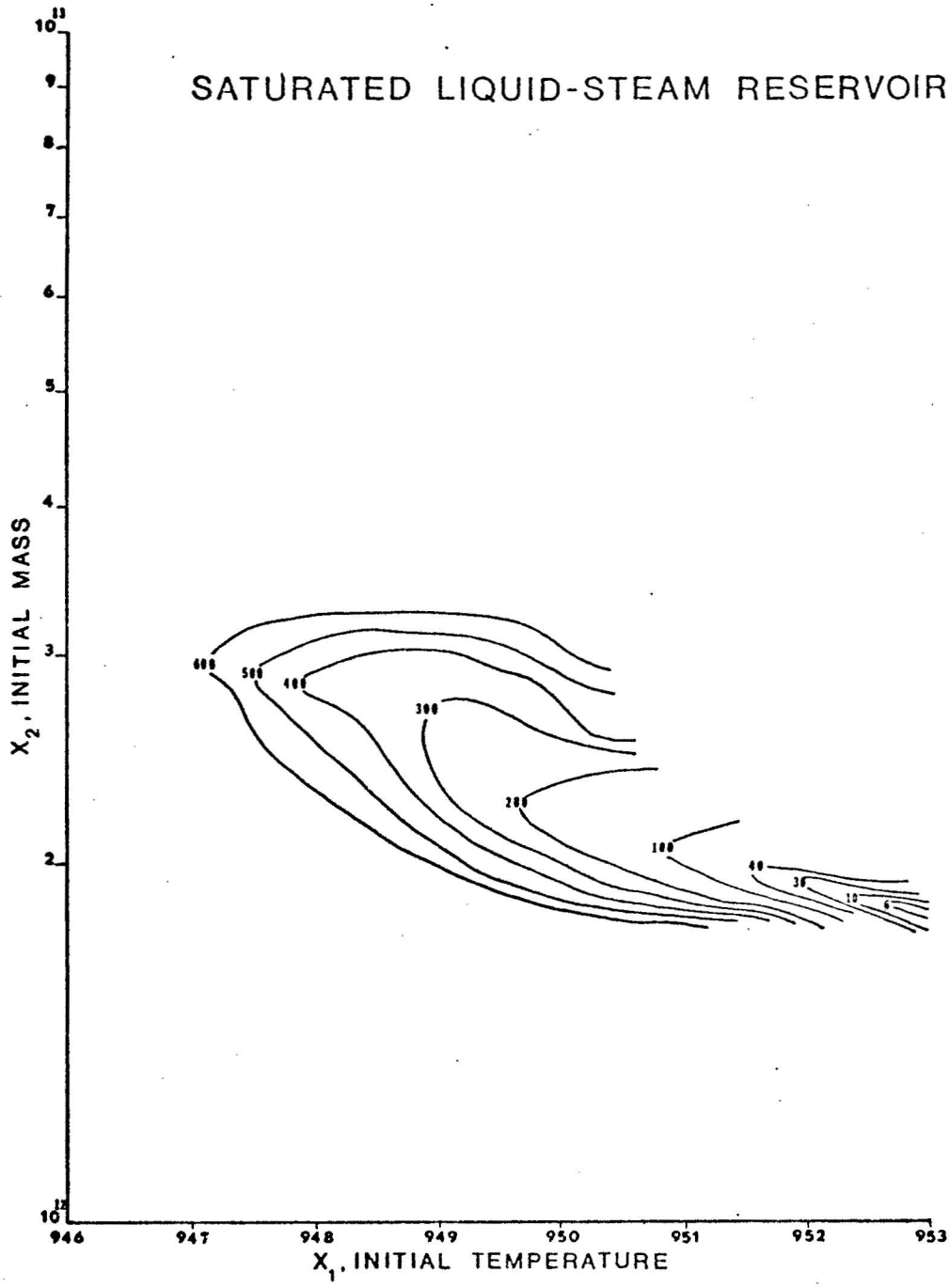


Figure 32. Contour Plot of Least Squares Function with Initial Steam Quality = 1.0

responsible for the variations.

The third parameter investigated was the initial steam quality (Table 17). Since the value is already constrained by definition (i.e. 0.0 to 1.0), only the upper constraint was examined.

One of the reservoir parameters analyzed was formation porosity (Table 18). A porosity of 20% resulted in a good curve fit. Porosities greater than 30% resulted in a trend of good curve fits. A least squares value of 1 was calculated for a porosity of 40%, but the figure was not taken seriously as 40% porosity is an unrealistic physical condition. This analysis shows that porosity is slightly sensitive to the calculation scheme.

The other reservoir parameter in question was rock density (Table 19). The results reveal that the final outcome is not sensitive to the reservoir rock density value. The range of values from 180 lb/ft^3 to 210 lb/ft^3 displayed good curve fits.

The optimum mass influx rate is 1.0×10^{10} lb/yr, starting at a value of 2.0×10^{10}lb (Table 20). All the mass influx rates greater than 1.0×10^{10} lb/yr had unacceptable curve fits. The least squares value decreased to 4 from 8, encouraging a better curve fit when a large mass influx is present.

Since influx enthalpy appears in the energy balance, influx temperature was also inspected. The least squares value showed better curve fits with the exception at 860.0°R. The curve fit values decreased from 8 to 1 (Table 21). It appears that the final outcome is not too sensitive to the influx temperature chosen.

Mass influx rate was checked again with an influx temperature of

560.0°R instead of 960.0°R (Table 22). As expected, a higher rate was found to be the maximum allowable rate at 1.0 X 10^{11} lb/yr. Examination of the energy balance equation (2) discloses that the product of mass influx and influx enthalpy is of main concern. When influx temperature is low, the mass influx rate will be greater to compensate for the lower enthalpy value, if a good least squares fit is desired.

V.3.3. Superheated Steam Reservoir

Examination of Table 23 revealed that P_i/Z_i (initial pressure, initial compressibility factor) has a moderate confidence range for the upper constraint (191.0 psia to 250.0 psia) and lower constraint (150.0 psia to 190.0 psia). There are low-high-low least squares values in each case. The variations are once again attributed to the optimization logic of BOX. In Figure 33 is illustrated the contour plot of the least squares equation as a function of P_i/Z_i versus initial mass. Like the other reservoir contour plots, a narrow ridge exists at some section in the plot. It is highly possible that the optimization scheme iterated about a narrow ridge, stopping it from further advancement.

In Tables 24 and 25 are displayed the sensitivity analyses for initial mass and the mass influx range, respectively. The confidence range is moderate compared to the other reservoirs studied. There is a low-high-low effect on the least squares values. Again this is probably due to the optimization scheme. The maximum allowable rate of mass influx is 1.0 X 10^9 lb/yr. Any rate greater than this will result in a bad curve fit.

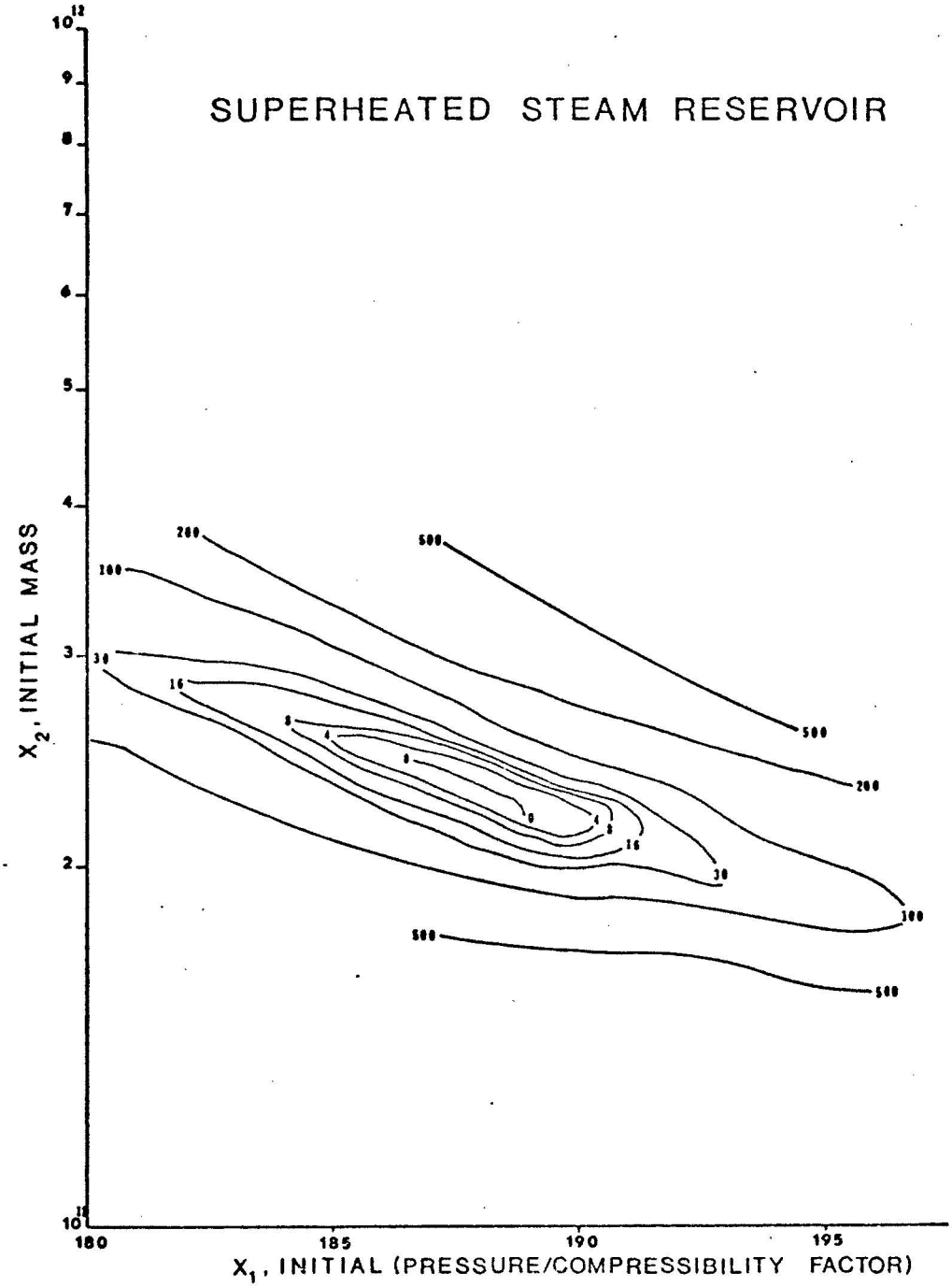


Figure 33. Contour Plot of Least Squares Function

VI. CONCLUSION

The HGP model results for the optimum initial parameters for the compressed liquid case verified the results produced by the Whiting-Ramey model. The superheated steam case was compared with Ramey's plots. The optimum initial parameters determined by the HGP model confirmed Ramey's estimated values. The HGP model successfully projected the performance of the geothermal reservoirs at different production rates.

The optimum mass influx rate tended to have better curve fits in performance matching and larger life expectancies for the geothermal reservoir in performance projections than with negligible mass influx. A comparison of the optimum initial parameters for each case revealed that the differences are relatively insignificant, although the differences are evident in the prediction plots.

It was found that the upper constraint of the initial mass parameter for each geothermal reservoir examined (compressed liquid, saturated liquid-steam, and superheated steam) was the most sensitive parameter in the performance matching with BOX. The magnitude of the initial mass value (10^9-10^{11}) in comparison with values of the other initial parameters (1-10^2) may be the contributing factor to its relative sensitivity in the optimization scheme. The upper constraint values of initial pressure, initial temperature, and initial (pressure/compressibility factor) are secondary in comparison with initial mass values, although selection of these values must be reasonable. The initial steam quality is, as mentioned before, constrained by definition. The starting points, in BOX, of the unknown initial parameters should be feasible.

In the case of the two-phase reservoir, rock density and influx temperature did not appear to be sensitive parameters, while formation porosity did show signs of sensitivity. The basic equations reveal that rock density and influx temperature do not play an active role in the calculation scheme, whereas formation porosity does. This active role may contribute to its relative sensitivity in the performance matching.

VI.1. Recommendations

It is recommended as a further study, since the sensitivity analysis is essentially boundless, that other variations may be examined to obtain each parameter's true sensitivity. Also, the effects of higher solids concentration (>3%) and non-condensable gases on the thermodynamic properties of water and steam should be investigated. This work may have to be done much later because of the limited information presently available in their respective fields.

APPENDICES

APPENDIX A

COMPRESSED LIQUID CALCULATIONS

Energy balance equation (2) reduces to (23) when Q_s=0.0 and isothermal conditions are assumed

$$W_c H_c = W_i H_i - W_p H_p + W_e H_e - W_L H_L \tag{23}$$

By substituting the mass balance equation (1) into (23) and rearranging

$$H_c = (W_i H_i - W_p H_p + W_e H_e - W_L H_L)/(W_i - W_p - W_L + W_e) \tag{24}$$

Enthalpy equation (4) rearranges to

$$X_c = (H_c - H_f)/(H_g - H_f) \tag{25}$$

Volumetric balance equation (3) also is rearranged to

$$X_c = (V\phi - V_f W_c)/(W_c(V_g - V_f)) \tag{26}$$

Equating equations (25) and (26) to

$$(H_c - H_f)/(H_g - H_f) = (V\phi - V_f W_c)/(W_c(V_g - V_f)) \tag{27}$$

or

$$W_c(H_c - H_f) = (H_g - H_f)(V\phi - V_f W_c)/(V_g - V_f)) \tag{28}$$

Substituting mass balance equation (1) and (24) into (28) gives

$$\begin{aligned}&(((W_i H_i - W_p H_p + W_e H_e - W_L H_L)/W_c) - H_f)(W_i - W_p + W_e - \\ &W_L) = (H_g - H_f)(V\phi - V_f(W_i - W_p + W_e - W_L))/ \\ &(V_g - V_f)\end{aligned} \tag{29}$$

There is a relationship between W_i and V

$$W_i = V\phi((S_{wi}/V_{fi}) + ((1 - S_{wi})/V_{gi})) \tag{30}$$

where S_{wi} = initial hot water saturation

V_{fi} = initial specific volume of saturated liquid, ft^3/lb

V_{gi} = initial specific volume of saturated vapor, ft^3/lb

Since S_{wi} = 1, equation (30) reduces to

$$W_i = V\phi/V_{fi} \tag{31}$$

or

$$V\phi = W_i V_{fi} \tag{32}$$

Substituting (32) into (29) gives

$$(W_i H_i - W_p H_p + W_e H_e - W_L H_L) - (W_i H_f - W_p H_f + W_e H_f - W_L H_f) = (H_g - H_f)(W_i V_{fi} - (W_i V_f - W_p V_f + W_e V_f - W_L V_f))/(V_g - V_f) \tag{33}$$

Assuming $H_p = H_i = H_e = H_L = H_f$, equation (33) reduces to

$$0 = (H_g - H_f)(W_i V_{fi} - (W_i V_f - W_p V_f + W_e V_f - W_L V_f))/(V_g - V_f) \tag{34}$$

Dividing by $(H_g - H_f)/(V_g - V_f)$ and substituting V_L for V_f and V_{Li} for V_{fi} gives

$$W_p V_L = W_i(V_L - V_{Li}) - W_L V_L + W_e V_L \tag{35}$$

Equation (35) is rearranged finally to equation (14)

* The preceding calculations was adapted from a report by Ramey [34]

APPENDIX B

COMPARISON PLOTS

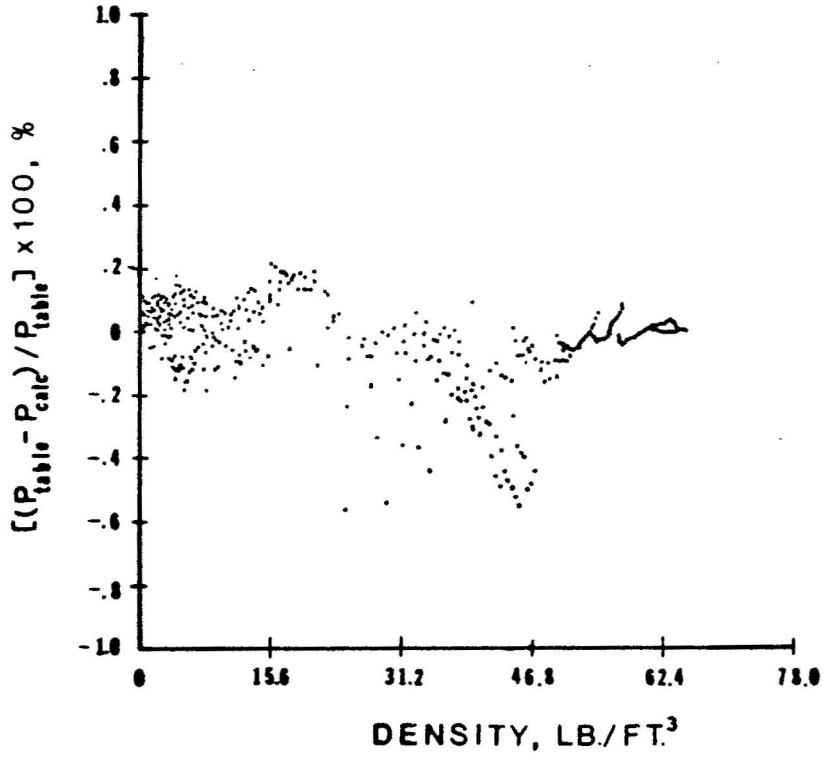


Figure 34. Density Differences as a Function of Density [26]

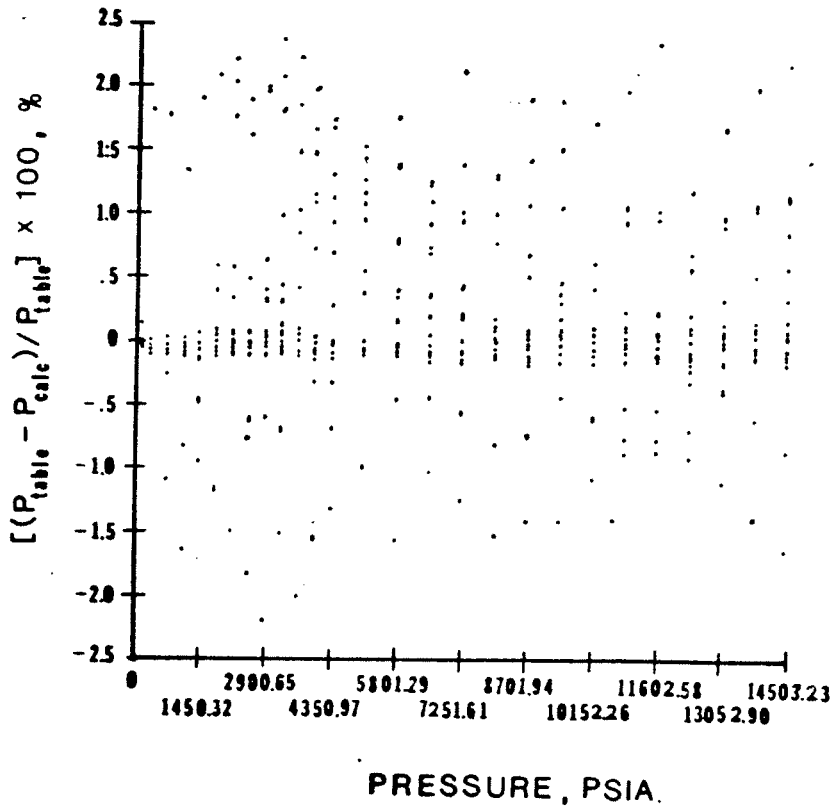


Figure 35. Pressure Differences as a Function of Pressure [26]

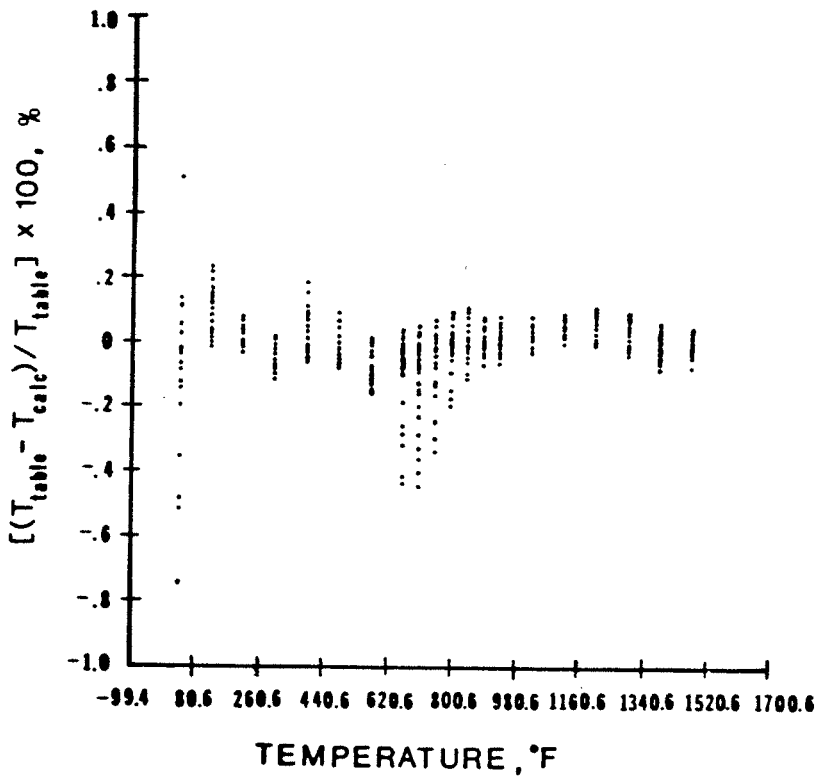


Figure 36. Temperature Differences as a Function of Temperature [26]

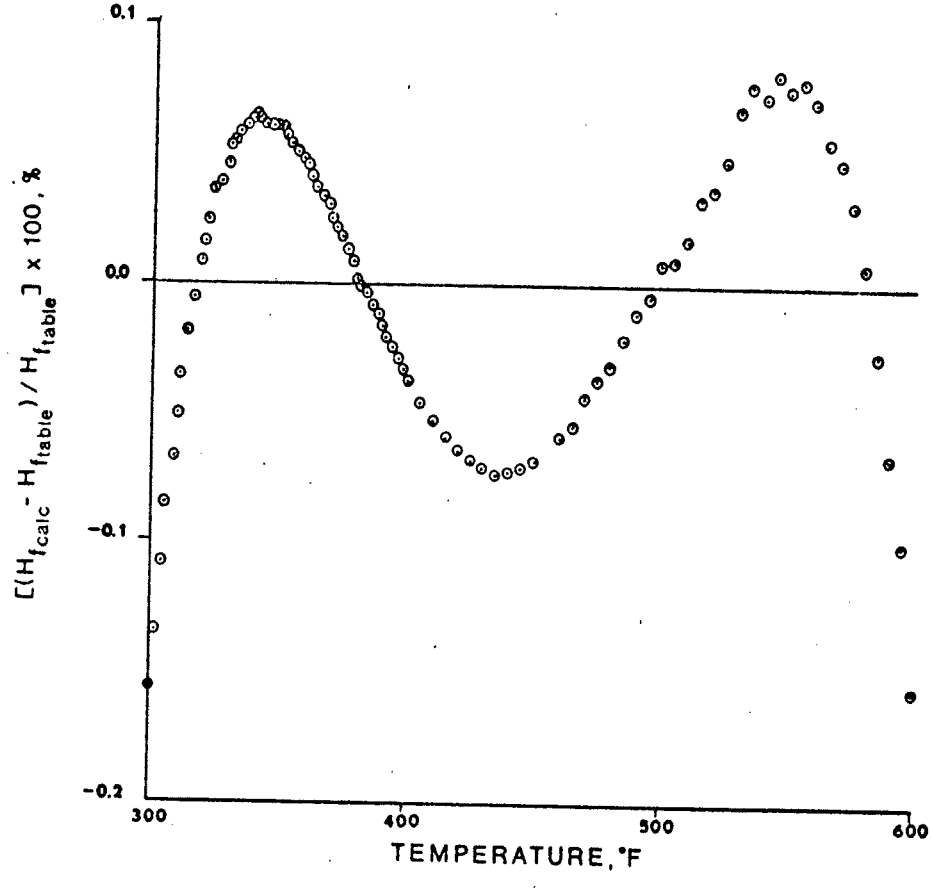


Figure 37. Enthalpy Differences of Saturated Liquid as a Function of Temperature

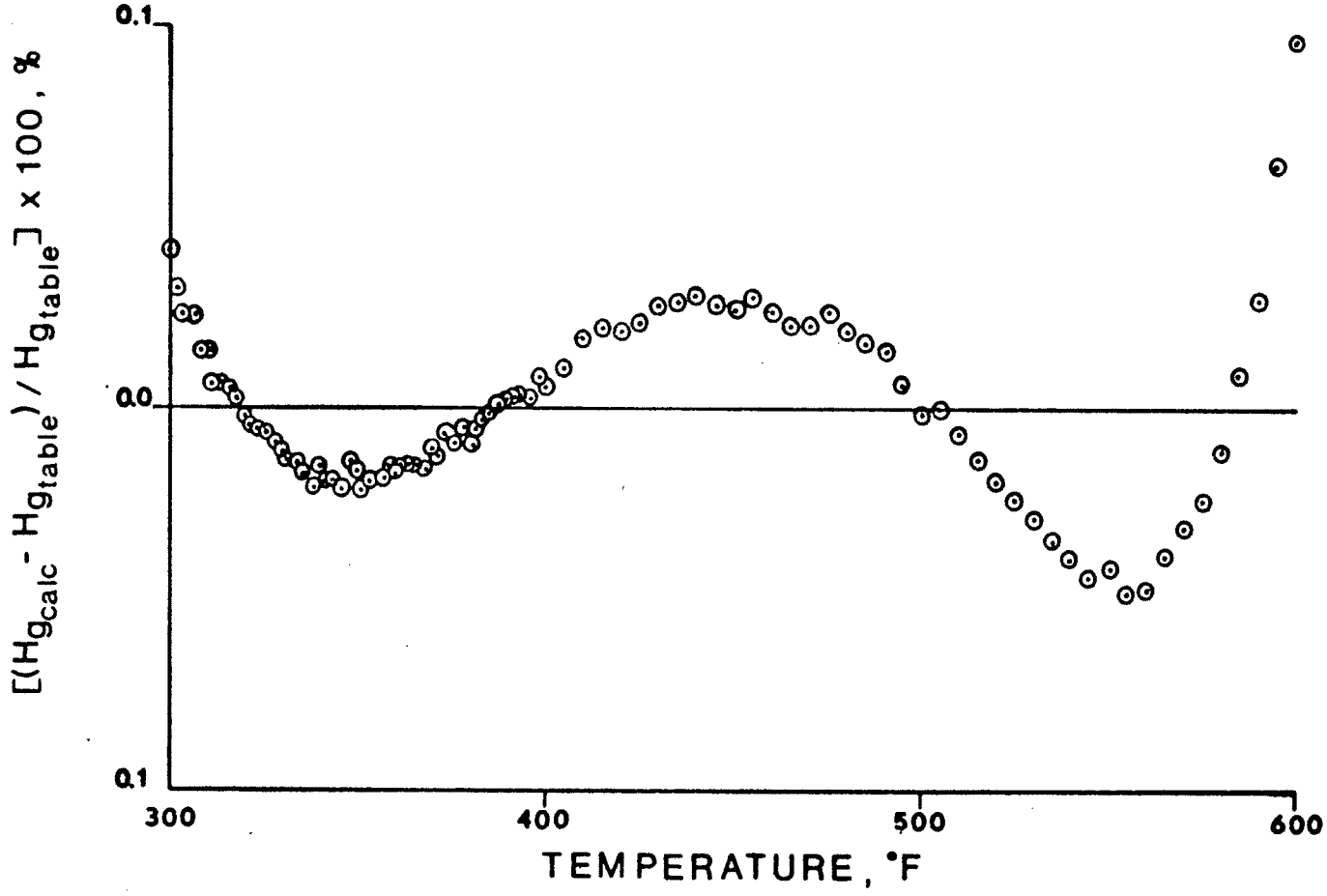


Figure 38. Enthalpy Differences of Saturated Vapor as a Function of Temperature

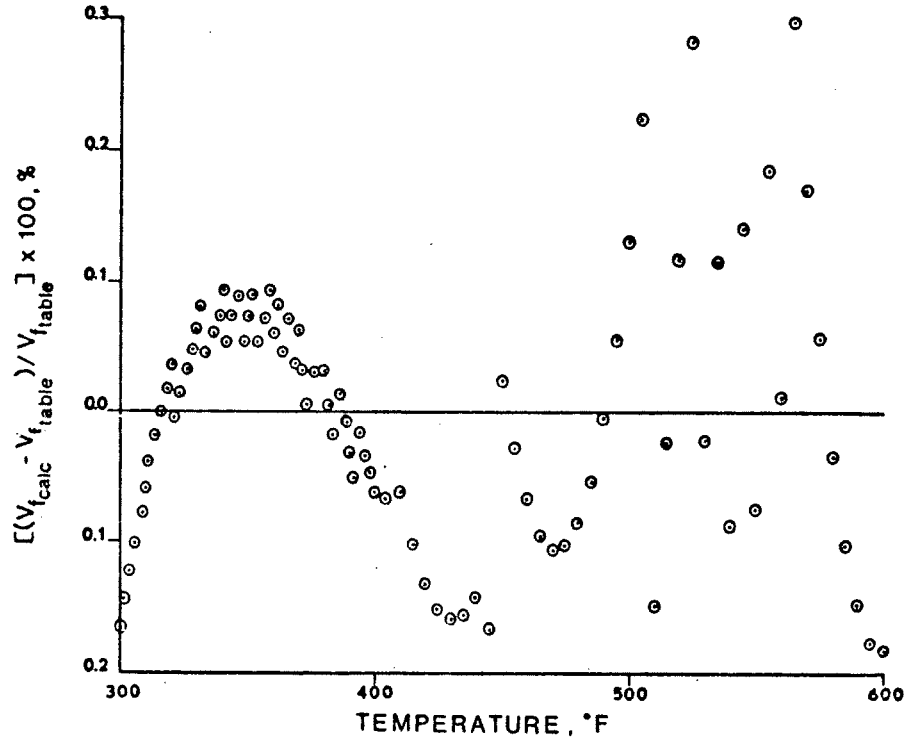


Figure 39. Specific Volume Differences of Saturated Liquid as a Function of Temperature

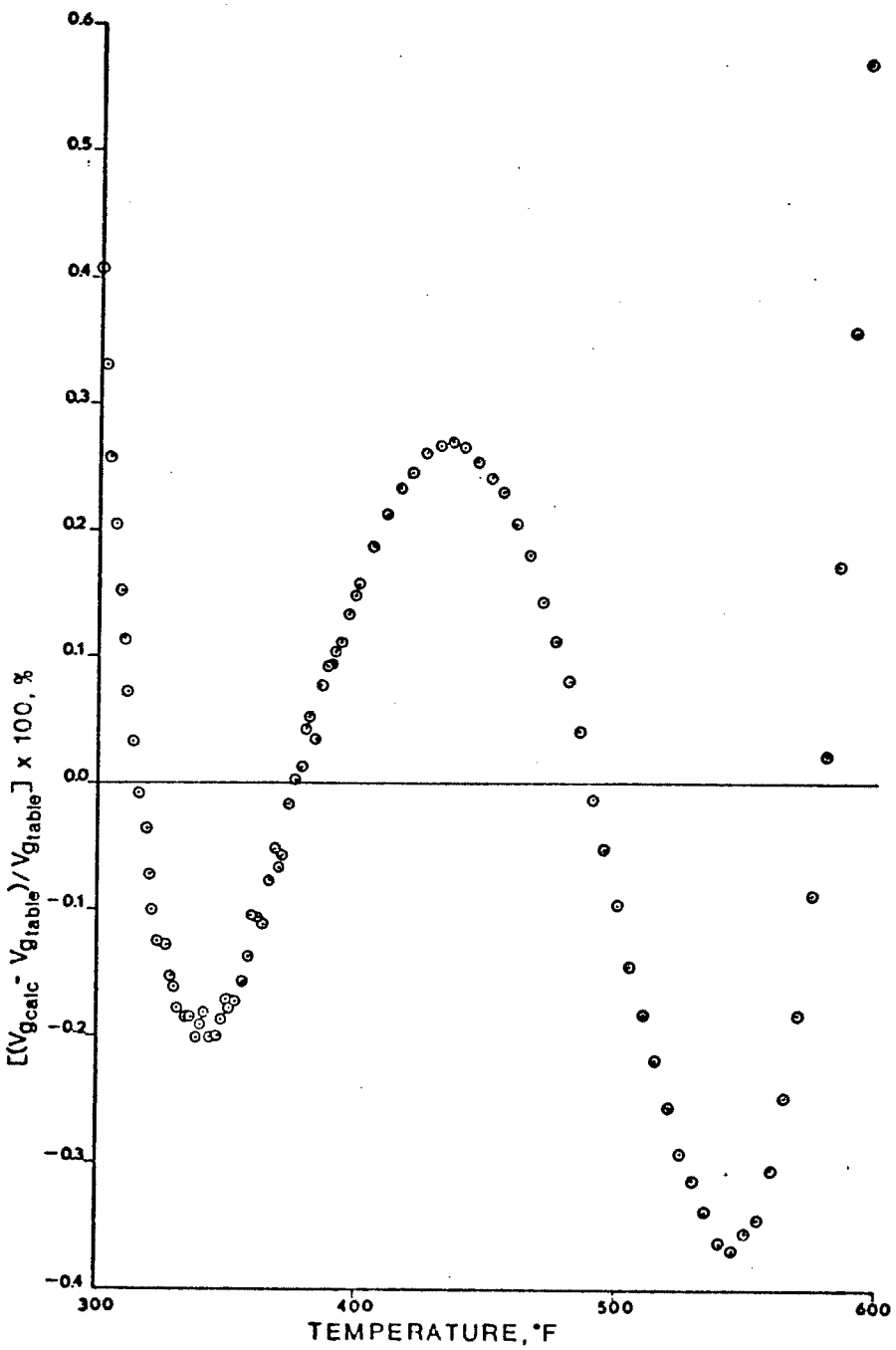


Figure 40. Specific Volume Differences of Saturated Vapor as a Function of Temperature

APPENDIX C

SENSITIVITY ANALYSIS TABLES

Table 12. Sensitivity Analysis of Initial Pressure for a Compressed Liquid Reservoir

starting value	lower constraint	upper constraint	optimum value, P_1	least squares value
750.0	724.7	750.0	738.32749	23,223
750.0	724.7	760.0	740.34061	21,975
750.0	724.7	775.0	772.08565	105
750.0	724.7	800.0	772.38813	105
750.0	724.7	825.0	771.86340	106
750.0	724.7	850.0	772.84808	105
750.0	724.7	875.0	769.60197	122
750.0	724.7	900.0	771.89778	106
750.0	724.7	950.0	773.28269	105
750.0	724.7	1000.0	772.94806	105
750.0	724.7	1500.0	743.92035	835
750.0	700.0	800.0	729.17921	16,066
750.0	710.0	800.0	772.23683	106
750.0	730.0	800.0	772.32675	105
750.0	750.0	800.0	772.12643	106
790.0	770.0	800.0	782.19101	57,431
790.0	780.0	800.0	780.00000	158

Table 13. Sensitivity Analysis of Initial Mass for a Compressed Liquid Reservoir

starting value	lower constraint	upper constraint	optimum value, W_1	least squares value
5.0×10^{13}	1.0×10^{13}	1.0×10^{14}	9.9999990×10^{13}	200,663
1.0×10^{15}	1.0×10^{13}	1.0×10^{15}	5.4641436×10^{14}	107
1.0×10^{15}	1.0×10^{13}	1.0×10^{16}	5.4231637×10^{14}	105
1.0×10^{15}	1.0×10^{13}	1.0×10^{17}	5.4198157×10^{14}	105
1.0×10^{15}	1.0×10^{13}	1.0×10^{18}	1.0000000×10^{17}	23,118
1.0×10^{15}	1.0×10^{13}	1.0×10^{19}	1.0000000×10^{18}	23,935
1.0×10^{15}	1.0×10^{10}	1.0×10^{17}	*	*
1.0×10^{15}	1.0×10^{11}	1.0×10^{17}	*	*
1.0×10^{15}	1.0×10^{12}	1.0×10^{17}	5.3704939×10^{14}	109
1.0×10^{15}	1.0×10^{14}	1.0×10^{17}	5.3806846×10^{14}	105
1.0×10^{15}	1.0×10^{15}	1.0×10^{17}	1.0000000×10^{15}	2,144

* error statement, no values printed

Table 14. Sensitivity Analysis of Mass Influx for a Compressed Liquid Reservoir

starting value	annual influx rate	optimum value, P_1	optimum value, W_1	least squares value
1.0	1.0	772.388130	$5.41981569 \times 10^{14}$	106
1.0×10^{5}	1.0×10^{5}	772.388130	$5.41981569 \times 10^{14}$	105
1.0×10^{7}	1.0×10^{7}	770.868157	$5.51227569 \times 10^{14}$	107
1.0×10^{9}	0.5×10^{9}	773.572606	$5.29927818 \times 10^{14}$	107
1.0×10^{9}	1.0×10^{9}	771.798882	$5.40379330 \times 10^{14}$	102
5.0×10^{9}	0.5×10^{9}	770.618411	$5.44492464 \times 10^{14}$	105
7.0×10^{9}	0.5×10^{9}	770.629973	$5.43295274 \times 10^{14}$	105
1.0×10^{10}	0.5×10^{10}	772.030399	$5.16438754 \times 10^{14}$	92
1.0×10^{10}	1.0×10^{10}	773.879926	$4.87952480 \times 10^{14}$	80
5.0×10^{10}	0.5×10^{10}	763.531849	$5.15181394 \times 10^{14}$	93
7.0×10^{10}	0.5×10^{10}	759.597863	$5.09612454 \times 10^{14}$	94
9.0×10^{10}	0.5×10^{10}	738.712937	$3.86052154 \times 10^{15}$	18,608
1.0×10^{11}	0.5×10^{11}	738.712937	$3.86052154 \times 10^{15}$	20,096
1.0×10^{11}	1.0×10^{11}	724.709951	$2.01632200 \times 10^{14}$	6,569
1.0×10^{12}	1.0×10^{12}	724.709951	$1.00000000 \times 10^{17}$	19,322
1.0×10^{13}	1.0×10^{13}	724.709951	$1.00000000 \times 10^{17}$	53,720

Table 15. Sensitivity Analysis of Initial Temperature for a Saturated Liquid-Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, T_I	least squares value
930.0	800.0	900.0	899.990000	196,387
930.0	800.0	950.0	949.456127	258
930.0	800.0	975.0	950.310798	158
930.0	800.0	990.0	952.469664	6
930.0	800.0	1000.0	952.620676	6
930.0	800.0	1025.0	951.987601	12
930.0	800.0	1060.0	946.491248	365
930.0	800.0	1100.0	965.465719	46,677
930.0	760.0	1000.0	949.741209	308
930.0	780.0	1000.0	952.808023	8
930.0	820.0	1000.0	951.606620	43
930.0	860.0	1000.0	946.400644	627
930.0	900.0	1000.0	947.427326	484
930.0	950.0	1000.0	954.208000	6,967
930.0	975.0	1000.0	975.010000	120,424

Table 16. Sensitivity Analysis of Initial Mass for a Saturated Liquid-Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, W_i	least squares value
1.0×10^{13}	1.5×10^{12}	6.50×10^{12}	$3.12747028 \times 10^{12}$	430
1.0×10^{13}	1.5×10^{12}	7.00×10^{12}	$2.13808999 \times 10^{12}$	173
1.0×10^{13}	1.5×10^{12}	7.25×10^{12}	$6.41517998 \times 10^{12}$	548
1.0×10^{13}	1.5×10^{12}	7.40×10^{12}	$3.41802360 \times 10^{12}$	412
1.0×10^{13}	1.5×10^{12}	7.48×10^{12}	$2.05042568 \times 10^{12}$	101
1.0×10^{13}	1.5×10^{12}	7.49×10^{12}	$1.83196469 \times 10^{12}$	6
1.0×10^{13}	1.5×10^{12}	7.50×10^{12}	$1.83235074 \times 10^{12}$	6
1.0×10^{13}	1.5×10^{12}	7.51×10^{12}	$1.86363221 \times 10^{12}$	15
1.0×10^{13}	1.5×10^{12}	7.60×10^{12}	$4.37897524 \times 10^{12}$	448
1.0×10^{13}	1.5×10^{12}	7.75×10^{12}	$4.53035948 \times 10^{12}$	337
1.0×10^{13}	1.5×10^{12}	8.50×10^{12}	$2.08385094 \times 10^{12}$	115
1.0×10^{13}	1.5×10^{12}	1.50×10^{13}	$3.06860061 \times 10^{12}$	369
1.0×10^{13}	1.5×10^{12}	1.00×10^{14}	$3.63461858 \times 10^{12}$	584
1.0×10^{13}	1.5×10^{12}	5.50×10^{15}	$5.15045211 \times 10^{12}$	476

Table 16. (Continued) Sensitivity Analysis of Initial Mass for a Saturated Liquid-Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, W_i	least squares value
1.0×10^{13}	1.30×10^{12}	7.50×10^{12}	*	*
1.0×10^{13}	1.35×10^{12}	7.50×10^{12}	$1.85862249 \times 10^{12}$	6
1.0×10^{13}	1.40×10^{12}	7.50×10^{12}	$1.90931943 \times 10^{12}$	13
1.0×10^{13}	1.45×10^{12}	7.50×10^{12}	$4.31049938 \times 10^{12}$	452
1.0×10^{13}	1.75×10^{12}	7.50×10^{12}	$2.44119431 \times 10^{12}$	515
1.0×10^{13}	2.00×10^{12}	7.50×10^{12}	$2.13825731 \times 10^{12}$	136

* error statememt, no values printed

Table 17. Sensitivity Analysis of Initial Steam Quality for a Saturated Liquid-Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, X_i	least squares value
0.1	0.0	1.00	0.017004	6
0.1	0.0	0.75	0.000644	505
0.1	0.0	0.50	0.000583	126
0.1	0.0	0.25	0.003769	277

Table 18. Sensitivity Analysis of Formation Porosity for a Saturated Liquid-Steam Reservoir

porosity	optimum value, T_i	optimum value, W_i	optimum value, X_i	least squares value
0.10	946.178541	$7.05422545 \times 10^{12}$	0.470236	556
0.15	947.255100	$6.42408671 \times 10^{12}$	0.076197	515
0.20	952.620676	$1.83235074 \times 10^{12}$	0.017004	6
0.25	950.933252	$3.03416067 \times 10^{12}$	0.039722	929
0.30	954.028091	$2.05171431 \times 10^{12}$	0.064674	25
0.35	954.470940	$2.12402683 \times 10^{12}$	0.034644	24
0.40	955.374322	$2.29841283 \times 10^{12}$	0.179955	1

Table 19. Sensitivity Analysis of Rock Density for a Saturated Liquid-Steam Reservoir

rock density	optimum value, T_i	optimum value, W_i	optimum value, X_i	least squares value
150.0	950.577142	$2.90672501 \times 10^{12}$	0.077004	513
180.0	952.866094	$1.84652664 \times 10^{12}$	0.028605	6
190.0	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
200.0	952.748282	$1.83454438 \times 10^{12}$	0.129192	7
210.0	952.477309	$1.82736169 \times 10^{12}$	0.083880	6
250.0	951.851818	$1.80087978 \times 10^{12}$	0.216515	11

Table 20. Sensitivity Analysis of Mass Influx for a Saturated Liquid-Steam Reservoir

starting value	annual influx rate	optimum value, T_i	optimum value, W_i	optimum value, X_i	least squares value
1.0	1.0	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
1.0×10^{4}	1.0×10^{4}	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
1.0×10^{7}	1.0×10^{7}	952.514872	$1.85109958 \times 10^{12}$	0.042272	7
5.0×10^{7}	1.0×10^{7}	952.514872	$1.85109958 \times 10^{12}$	0.042272	7
1.0×10^{8}	1.0×10^{8}	952.790551	$1.85341818 \times 10^{12}$	0.114283	4
5.0×10^{8}	1.0×10^{8}	952.769693	$1.85738368 \times 10^{12}$	0.092481	6
1.0×10^{9}	1.0×10^{9}	952.787525	$1.84389996 \times 10^{12}$	0.087523	5
1.0×10^{10}	1.0×10^{10}	952.762186	$1.76101814 \times 10^{12}$	0.000177	7
2.0×10^{10}	1.0×10^{10}	952.739672	$1.77168640 \times 10^{12}$	0.014552	4
3.0×10^{10}	1.0×10^{10}	947.032294	$7.22155170 \times 10^{12}$	0.067509	495
1.0×10^{11}	1.0×10^{11}	953.356062	$1.50044827 \times 10^{12}$	0.104199	123
1.0×10^{12}	1.0×10^{12}	972.010428	$7.16274223 \times 10^{12}$	0.052148	96,195

influx temperature = 960°R

Table 21. Sensitivity Analysis of Influx Temperature for a Saturated Liquid-Steam Reservoir

influx temperature	optimum value, T_i	optimum value, W_i	optimum value, X_i	least squares value
960.0	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
860.0	947.376883	$5.42715247 \times 10^{12}$	0.013869	472
760.0	952.827835	$1.78681764 \times 10^{12}$	0.000339	3
660.0	953.181239	$1.78221487 \times 10^{12}$	0.000464	4
560.0	953.067841	$1.81811790 \times 10^{12}$	0.000100	2
500.0	953.126687	$1.82470545 \times 10^{12}$	0.000100	1

mass influx rate = 1.0×10^{10} lb/yr (starting at 2.0×10^{10} lb)

Table 22. Sensitivity Analysis of Mass Influx for a Saturated Liquid-Steam Reservoir

starting value	annual influx rate	optimum value, T_i	optimum value, W_i	optimum value, X_i	least squares value
1.0	1.0	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
1.0×10^{4}	1.0×10^{4}	952.518912	$1.87592409 \times 10^{12}$	0.078475	8
1.0×10^{8}	1.0×10^{8}	952.760560	$1.85592192 \times 10^{12}$	0.121394	5
1.0×10^{10}	1.0×10^{10}	953.049749	$1.81601504 \times 10^{12}$	0.096218	3
3.0×10^{10}	1.0×10^{10}	953.278620	$1.80955530 \times 10^{12}$	0.000104	2
1.0×10^{11}	1.0×10^{11}	955.095157	$1.58620470 \times 10^{12}$	0.075555	0
1.0×10^{12}	1.0×10^{12}	965.303948	$6.68711470 \times 10^{12}$	0.033495	921
1.0×10^{13}	1.0×10^{13}	988.591642	$4.08633524 \times 10^{12}$	0.505553	43,506

influx temperature = 560°R

Table 23. Sensitivity Analysis of Initial (Pressure/Compressibility Factor) for a Superheated Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, P_i/Z_i	least squares value
170.0	165.0	175.0	174.99000	95
170.0	165.0	180.0	179.99000	34
190.0	165.0	191.0	186.94292	1
190.0	165.0	200.0	188.13560	0
190.0	165.0	210.0	188.75563	0
190.0	165.0	215.0	185.95661	2
190.0	165.0	220.0	183.14578	111
190.0	165.0	225.0	188.16259	0
190.0	165.0	250.0	188.57944	0
190.0	165.0	275.0	237.59626	8,245
190.0	165.0	300.0	172.89332	140
190.0	150.0	225.0	187.94913	0
190.0	160.0	225.0	187.27178	90
190.0	170.0	225.0	188.08131	0
190.0	180.0	225.0	188.10581	0
190.0	190.0	225.0	190.01000	2
200.0	200.0	225.0	200.01000	91

Table 24. Sensitivity Analysis of Initial Mass for a Superheated Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, W_i	least squares value
1.0×10^{11}	5.0×10^{10}	1.0×10^{11}	9.9999269×10^{10}	1,953
1.0×10^{11}	5.0×10^{10}	5.0×10^{11}	2.3119401×10^{11}	0
1.0×10^{11}	5.0×10^{10}	6.0×10^{11}	2.4412738×10^{11}	1
1.0×10^{11}	5.0×10^{10}	7.5×10^{11}	2.5750694×10^{11}	1,432
1.0×10^{11}	5.0×10^{10}	8.5×10^{11}	2.8854179×10^{11}	1,997
1.0×10^{11}	5.0×10^{10}	1.0×10^{12}	3.3509406×10^{11}	2,775
1.0×10^{11}	5.0×10^{10}	2.5×10^{12}	2.3534086×10^{11}	0
1.0×10^{11}	5.0×10^{10}	5.0×10^{12}	2.3226032×10^{11}	1
1.0×10^{11}	5.0×10^{10}	1.0×10^{13}	9.9371456×10^{11}	304
1.0×10^{11}	5.0×10^{10}	5.0×10^{13}	1.0515033×10^{12}	304
1.0×10^{11}	5.0×10^{10}	1.0×10^{14}	1.0108717×10^{12}	304
1.0×10^{11}	5.0×10^{10}	1.0×10^{15}	3.2703187×10^{14}	500
1.0×10^{11}	5.0×10^{10}	1.0×10^{16}	3.6025424×10^{15}	500
1.0×10^{11}	5.0×10^{9}	5.0×10^{11}	2.2927008×10^{11}	0

Table 24. (Continued) Sensitivity Analysis of Initial Mass for a Superheated Steam Reservoir

starting value	lower constraint	upper constraint	optimum value, W_1	least squares value
1.0×10^{11}	5.0×10^{9}	2.5×10^{12}	9.9050409×10^{11}	304
7.5×10^{11}	5.0×10^{11}	2.5×10^{12}	8.8401541×10^{11}	304

Table 25. Sensitivity Analysis of Mass Influx for a Superheated Steam Reservoir

starting value	annual influx rate	optimum value, P_i/Z_i	optimum value, W_i	least squares value
1.0	1.0	188.162590	2.3119401×10^{11}	0
1.0×10^{5}	1.0×10^{5}	188.162587	2.3119401×10^{11}	0
1.0×10^{7}	1.0×10^{7}	187.351720	2.3736176×10^{11}	0
1.0×10^{8}	1.0×10^{8}	188.236951	2.2175536×10^{11}	2
1.0×10^{9}	0.5×10^{9}	188.394489	2.0928332×10^{11}	0
1.0×10^{9}	1.0×10^{9}	191.320409	1.8274845×10^{11}	0
5.0×10^{9}	0.5×10^{9}	205.285446	1.9530474×10^{11}	1,701
1.0×10^{10}	1.0×10^{10}	165.010000	4.9999900×10^{11}	1,040
1.0×10^{11}	1.0×10^{11}	165.010000	4.9999900×10^{11}	128,362
1.0×10^{12}	1.0×10^{12}	165.010000	4.9999900×10^{11}	13,518,514

APPENDIX D

COMPUTER PROGRAM BOX

USER'S GUIDE, LISTING, AND PRINTOUT

BOX User's Guide

Program Description

1. Usage:

The program consists of a main program and six subroutines (CONSX, CHEK, CENTR, FUNK, CONST, and WASP). Initial quesses of the independent variables, random numbers, optimization control parameters, production data, reservoir properties, and a printer code designation are passed to the subroutines from the main program. The final function and initial parameter values are transferred to the main program for printout.

2. Subroutines Required:

SUBROUTINE CONSX (N,M,ITMAX,ALPHA,BETA,GAMMA,DELTA,X,R,F, IT,IEV2,G,H,IPRINT,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,KN,XC, DENSS,QS,WL,WE,TE,X2) is called from the main program and coordinates all special purpose subroutines (CHEK, CENTR, FUNK, and CONST).

SUBROUTINE CHEK (N,M,KN,X,G,H,I,KCODE,XC,DELTA,K1) checks all points against explicit and implicit constraints, applying corrections if violations are found.

SUBROUTINE FUNK (N,M,KN,X,F,I,WP,PBAR,PC,KR,KCOND,JK,TI, TC,POR,DENSS,QS,WL,WE,TE,X2) calculates the least squares value for the appropriate geothermal reservoir and calls SUBROUTINE WASP for the thermodynamic properties of steam and water.

SUBROUTINE CONST (N,M,KN,X,G,H,I) specifies explicit and

implicit constraint limits (user supplied). Explicit constraints go first in order.

SUBROUTINE WASP (KS,KP,T,P,D,H,KR) calculates the thermodynamic properties of water and steam for all phases (User's Guide in Appendix F).

SUBROUTINE CENTR (N,M,KN,IEV1,XC,X,K1) calculates the centroid of the points.

3. Description of Parameters:

Defined in the main program (user supplied)

N	number of explicit independent variables (initial parameters)
M	number of sets of constraints
KN	number of points in complex
ITMAX	maximum number of iterations
IC	number of implicit constraints
KCOND	reservoir characteristic controller (=KR of WASP)
	=1 saturated liquid-steam reservoir
	=2 compressed liquid reservoir
	=3 superheated steam reservoir
ALPHA	reflection factor
BETA	convergence parameter
GAMMA	convergence parameter
DELTA	explicit constraint violation correction factor
IPRINT	code to control printing of intermediate iterations
	=0 suppresses printing until final solution

is obtained

=1 causes intermediate values to print on each iteration

X	independent variables (initial parameters)
R	random numbers between 0 and 1
JK	number of actual production data sets (data set = average reservoir pressure versus cumulative mass produced)
WP	actual cumulative mass produced
PBAR	actual average reservoir pressure
TI	initial reservoir temperature
TC	current reservoir temperature
WE	cumulative mass influx
WL	cumulative mass loss
QS	cumulative net heat conducted into the reservoir
POR	formation porosity
DENSS	rock density
TE	influx temperature

Defined in SUBROUTINE FUNK

F	objective function (least squares function)
VLI	initial liquid specific volume
V	reservoir bulk volume
WC	current mass in reservoir
VL	current liquid specific volume
X2	current steam quality
DLC	current liquid density

PC	calculated reservoir pressure
VVI	initial vapor specific volume
VV	current vapor specfic volume
Z	current compressibility factor
PPX	current (pressure/compressibility factor)
VGG	current vapor specific volume
HFI	initial saturated liquid enthalpy
HGI	initial saturated vapor enthalpy
VFI	initial saturated liquid specific volume
VGI	initial saturated vapor specific volume
HE	influx liquid enthalpy
SVOLI	initial saturated specific volume
HI	initial saturated enthalpy
T( )	current reservoir temperature
HF	current saturated liquid enthalpy
HG	current saturated vapor enthalpy
VF	current saturated liquid specific volume
VG	current saturated vapor specific volume
SPHT	specific heat of reservoir rock
HC	current saturated enthalpy
HP	enthalpy produced
HHL	enthalpy loss
Y	energy balance equation (set=0)
SPVOL	current saturated specific volume
DDD	current liquid density
LST	least squares value (=F)

Defined in SUBROUTINE CONSX

IT	iteration index
IEV1	index of point with minimum value
IEV2	index of point with maximum value
I	point index
K1	do-loop limit
KCODE	key used to determine if implicit constraints are provided

Defined in SUBROUTINE CONST (user supplied)

G	lower constraint
H	upper constraint

Defined in SUBROUTINE CENTR

XC	centroid value

Defined in SUBROUTINE WASP

Parameters defined in Appendix F

4. DIMENSION Requirements:

The DIMENSION statement in the main program and each subroutine (except WASP) should be modified according to the requirements of each particular problem. The program has been dimensioned to handle a value of JK=35. The parameters, included in the following DIMENSION statement, conform to the input parameter definitions above:

```
DIMENSION X(KN,M),R(KN,N),F(KN),G(M),H(M),XC(N),WP(JK),
  PBAR(JK),PC(JK),DELTA(N),WE(JK),WL(JK),QS(JK),VL(JK),
  DLC(JK),VV(JK),Z(JK),DGC(JK),T(200),Y(200)
```

5. Input Formats:

Initialize starting points in beginning of main program as follows: if

KCOND = 1 (saturated liquid-steam)

X(1,1) = initial temperature

X(1,2) = initial mass

X(1,3) = initial steam quality

KCOND = 2 (compressed liquid)

X(1,1) = initial pressure

X(1,2) = initial mass

KCOND = 3 (superheated steam)

X(1,1) = initial (pressure/compressibility factor)

X(1,2) = initial mass

where X(1,N) are feasible starting points

CARD TYPE	FORMAT	CONTENTS
1	8I5	N,M,KN,ITMAX,IC,IPRINT,KCOND,JK
2	2D10.4,I5	ALPHA,BETA,GAMMA
3	4D10.4	(DELTA(I),I=1,N)
4	8F10.4	(R(II,JJ),JJ=1,N)
5	5D16.8	(WP(MM),MM=1,JK)
6	8F10.4	(PBAR(NN),NN=1,JK)
7	2F10.4	TI,TC
if KCOND=1, set TI=TC=0.0		
8	8D10.4	(WE(L),L=1,JK)

CARD TYPE	FORMAT	CONTENTS
9	8D10.4	(WL(L),L=1,JK)
10	8D10.4	(QS(L),L=1,JK)
11	3D10.4	POR,DENSS,TE

6. Output:

The main program first prints out most of the values of the variables described in the previous section. SUBROUTINE CONSX provides intermediate output on each iteration, provided the user specifies IPRINT=1 on card type 1. If IPRINT =0, only the final solution is printed.

When the solution has converged to within the allowable range, or when the maximum number of iterations has been executed, the main program prints the final least squares value, the optimum initial parameters, the reservoir properties, and the match of reservoir pressures along with the mass produced, mass loss, mass influx, and heat influx.

7. Summary of User Requirements:

a. Determine the initial estimates for the optimum values of the independent variables as specified in Input Format. The initial points must satisfy the constraints.

b. Determine values for N,M,KN,ITMAX,IC,IPRINT,KCOND,JK, ALPHA,BETA,GAMMA,DELTA. Guidelines for specifying the parameters are as follows:

KN = 2N if N<5

KN = N+1 if N>5

ALPHA = 1.3

BETA = magnitude of function multiplied by 10^{-4}

GAMMA = 5

DELTA = magnitude of X_N vector multiplied by 10^{-4}

ITMAX = 500

IC = 0

c. Determine random numbers between 0 and 1.

d. Read in production data: WP,PBAR,TI,TC,WE,WL,QS and reservoir properties: POR,DENSS,TE. Parameter units must be expressed as shown in Table 26, KU=3.

e. Adjust DIMENSION and FORMAT statements as necessary.

f. Define H (upper constraint) and G (lower constraint) in SUBROUTINE CONST. Explicit constraints must precede implicit constraint.

8. Procedure to Find the Optimum Constraints:

a. The upper constraint of the initial mass is the most important constraint to vary. The least squares value varies greatly with different values of the constraint. The lower constraint may be set to the latest cumulative mass production value, WP_{JK}. Mass influx is assumed to be negligible.

b. The constraints of initial pressure, initial temperature, or initial (pressure/compressibility factor), depending on which case is being investigated, is of secondary interest compared to the initial mass, upper constraint. The lower constraint may be set to the latest known value

of $PBAR_{JK}$, in the case of a compressed liquid or superheated steam reservoir. For the two-phase case, a wide temperature range is acceptable.

c. In the two-phase case, the initial steam quality constraints are set to 0.0 and 1.0.

d. By varying the upper constraint of the initial mass, the user will find a least squares value low enough to suit the proposed criteria. When a least squares value is equal to zero, a perfect fit is encountered, but in this case it is close to a perfect fit. Once a good upper constraint is found, variations on the other parameters may be wanted.

e. Now, mass influx may be varied to find an influx of large magnitude that still produces a good fit. It is assumed that the influx rate will be constant. Influx temperature in the two-phase case may be altered also.

```
C
C
C        BOX-FIND THE OPTIMUM INITIAL CONDITIONS OF A GEOTHERMAL
C
C            RESERVOIR USING THE MASS-ENERGY BALANCE EQUTIONS
C
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER GAMMA
      DIMENSION X(6,3),R(6,3),F(6),G(3),H(3),XC(3),WP(35),PBAR(35),
     1          PC(35),DELTA(3),WE(35),WL(35),QS(35)
C
C
C        KCOND = 1 SATURATED LIQUID AND STEAM REGION
C
C                    X(I,1)=INITIAL TEMPERATURE
C                    X(I,2)=INITIAL MASS
C                    X(I,3)=INITIAL STEAM QUALITY
C
C              = 2 COMPRESSED LIQUID REGION
C
C                    X(I,1)=INITIAL PRESSURE
C                    X(I,2)=INITIAL MASS
C
C              = 3 SUPERHEATED STEAM REGION
C
C                    X(I,1)=INITIAL (PRESSURE/COMPRESSIBILITY FACTOR)
C                    X(I,2)=INITIAL MASS
C
C
C
C        INITIALIZE STARTING POINTS
C
      X(1,1)=
      X(1,2)=
         .
         .
         .
      X(1,N)=
C
C
C
      READ(5,1) N,M,KN,ITMAX,IC,IPRINT,KCOND,JK
    1 FORMAT(8I5)
      READ(5,2) ALPHA,BETA,GAMMA
    2 FORMAT(2D10.4,I5)
      READ(5,7) (DELTA(I),I=1,N)
    7 FORMAT(4D10.4)
C
      DO 100 II=2,KN
      READ(5,3) (R(II,JJ),JJ=1,N)
    3 FORMAT(8F10.4)
  100 CONTINUE
C
      READ(5,5) (WP(MM),MM=1,JK)
    5 FORMAT(5D16.8)
      READ(5,6) (PBAR(NN),NN=1,JK)
    6 FORMAT(8F10.4)
      READ(5,926) TI,TC
```

```
  926 FORMAT(2F10.4)
      READ(5,927) (WE(L),L=1,JK)
      READ(5,927) (WL(L),L=1,JK)
      READ(5,927) (QS(L),L=1,JK)
  927 FORMAT(9D10.4)
C
 1000 READ(5,928) POR,DENSS,TE
  928 FORMAT(3F10.5)
C
   90 WRITE(6,10)
   10 FORMAT(1H1,//,18X,24HCOMPLEX PROCEDURE OF BOX)
      WRITE(6,18)
   18 FORMAT(//,2X,10HPARAMETERS )
      WRITE(6,11) N,M,KN,ITMAX,IC,ALPHA,BETA,GAMMA
   11 FORMAT(//,2X,4HN = ,I2,3X,4HM = ,I2,3X,5HKN = ,I2,2X,8HITMAX = ,
     1I4,2X,5HIC = ,I2,//,2X,8HALPHA = ,F5.2,5X,7HBETA = ,F10.5,3X,
     28HGAMMA = ,I2)
      WRITE(6,929) (I,DELTA(I),I=1,N)
  929 FORMAT(/,3(2X,6HDELTA(,I2,4H) = ,1PD10.4,2X))
C
      IF (IPRINT) 40,50,40
   40 WRITE(6,12)
   12 FORMAT(//,2X,14HRANDOM NUMBERS)
      DO 200 J=2,KN
      WRITE(6,13) (J,I,R(J,I),I=1,N)
   13 FORMAT(/,3(2X,2HR(,I2,1H,,I2,4H) = ,F6.4,2X))
  200 CONTINUE
C
   50 CALL CONSX (N,M,KN,ITMAX,ALPHA,BETA,GAMMA,DELTA,X,R,F,IT,
     1IEV2,G,H,XC,IPRINT,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,WL,
     2WE,TE,X2)
C
      GO TO (110,120,130),KCOND
C
  110 WRITE(6,945)
  945 FORMAT(////,2X,'*** SATURATED LIQUID-STEAM RESERVOIR ***')
      GO TO 135
  120 WRITE(6,946)
  946 FORMAT(////,2X,'*** COMPRESSED LIQUID RESERVOIR ***')
      GO TO 135
  130 WRITE(6,947)
  947 FORMAT(////,2X,'*** SUPERHEATED STEAM RESERVOIR ***')
C
  135 IF (IT-ITMAX) 20,20,30
C
   20 WRITE(6,14) F(IEV2)
   14 FORMAT(///,2X,'FINAL LEAST SQUARES VALUE = ',1PD16.8)
      WRITE(6,15)
   15 FORMAT(///,6X,'FINAL VALUES')
C
      GO TO (22,23,24),KCOND
C
   22 WRITE(6,930) X(IEV2,1)
  930 FORMAT(/,2X,'INITIAL TEMPERATURE = ',F13.6)
      WRITE(6,931) X(IEV2,2)
  931 FORMAT(/,2X,'INITIAL MASS = ',1PD16.8)
      WRITE(6,932) X(IEV2,3)
  932 FORMAT(/,2X,'INITIAL STEAM QUALITY = ',F13.6)
      GO TO 25
```

```
C
   23 WRITE(6,930) TI
      WRITE(6,933) X(IEV2,1)
  933 FORMAT(/,2X,'INITIAL PRESSURE = ',F13.6)
      WRITE(6,934) X(IEV2,2)
  934 FORMAT(/,2X,'INITIAL MASS = ',1PD16.8)
      GO TO 25
C
   24 WRITE(6,930) TI
      WRITE(6,940) X(IEV2,1)
  940 FORMAT(/,2X,'INITIAL (PRESSURE/COMPRESSIBILITY FACTOR) = ',F13.6)
      WRITE(6,931) X(IEV2,2)
C
   25 WRITE(6,159)
  159 FORMAT(///,6X,'RESERVOIR PROPERTIES')
      WRITE(6,160) POR
  160 FORMAT(/,2X,'POROSITY = ',F13.5)
      WRITE(6,162) DENSS
  162 FORMAT(/,2X,'ROCK DENSITY = ',F13.5)
      WRITE(6,166) TE
  166 FORMAT(/,2X,'INFLUX TEMPERATURE = ',F13.5)
C
      WRITE(6,190)
  190 FORMAT(//,3X,'ACTUAL PRESSURE',3X,'CALCULATED PRESSURE',4X,'MASS P
     1RODUCED',5X,'MASS INFLUX',7X,'MASS LOST',7X,'HEAT INFLUX')
      DO 900 L=1,JK
      WRITE(6,191) PBAR(L),PC(L),WP(L),WE(L),WL(L),QS(L)
  191 FORMAT(/,2X,F13.5,7X,F13.5,7X,1PD15.7,2X,D15.7,2X,D15.7,2X,D15.7)
  900 CONTINUE
C
      GO TO 999
C
   30 WRITE(6,17) ITMAX
   17 FORMAT(///,2X,38HTHE NUMBER OF ITERATIONS HAS EXCEEDED ,I4,10X,
     118HPROGRAM TERMINATED)
C
  999 STOP
      END



      SUBROUTINE CONSX (N,M,KN,ITMAX,ALPHA,BETA,GAMMA,DELTA,X,R,F,
     1IT,IEV2,G,H,XC,IPRINT,WP,PBAR,PC,KP,KCOND,JK,TI,TC,POR,DENSS,QS,
     2WL,WE,TE,X2)
      IMPLICIT REAL*8 (A-H,O-Z)
C
C        COORDINATES SPECIAL PURPOSE SUBROUTINES
C
C        ARGUMENT LIST
C
C        IT     = ITERATION INDEX
C        IEV1   = INDEX OF POINT WITH MINIMUM FUNCTION VALUE
C        IEV2   = INDEX OF POINT WITH MAXIMUM FUNCTION VALUE
C        I      = POINT INDEX
C        KCODE  = CONTROL KEY USED TO DETERMINE IF IMPLICIT CONSTRAINTS
C                 ARE PROVIDED
C        K1     = DO LOOP LIMIT
C
```

```
C        ALL OTHERS PREVIOUSLY DEFINED IN MAIN LINE
C
      DIMENSION X(6,3),R(6,3),F(6),G(3),H(3),XC(3),WP(35),PBAR(35),
     1          PC(35),DELTA(3),WE(35),WL(35),QS(35)
      INTEGER GAMMA
C
      IT = 1
      KCODE = 0
      IF (M-N) 20,20,10
   10 KCODE = 1
   20 CONTINUE
C
      DO 40 II=2,KN
      DO 30 J=1,N
   30 X(II,J) = 0.0
   40 CONTINUE
C
C        CALCULATE COMPLEX POINTS AND CHECK AGAINST CONSTRAINTS
C
      DO 65 II=2,KN
      DO 50 J=1,N
      I = II
C
      CALL CONST (N,M,KN,X,G,H,I)
C
      X(II,J) = G(J) + R(II,J)*(H(J)-G(J))
   50 CONTINUE
      K1 = II
C
      CALL CHEK  (N,M,KN,X,G,H,I,KCODE,XC,DELTA,K1)
C
      IF (II-2) 51,51,55
   51 IF (IPRINT) 52,65,52
C
   52 WRITE(6,18)
   18 FORMAT(//,2X,30HCOORDINATES OF INITIAL COMPLEX)
      IO = 1
      WRITE(6,19) (IO,J,X(IO,J),J=1,N)
   19 FORMAT (/,3(2X,2HX(,I2,1H,,I2,4H) = ,1PD13.6))
C
   55 IF (IPRINT) 56,65,56
   56 WRITE(6,19) (II,J,X(II,J),J=1,N)
   65 CONTINUE
C
      K1 = KN
      DO 70 I=1,KN
C
      CALL FUNK (N,M,KN,X,F,I,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1WL,WE,TE,X2)
C
   70 CONTINUE
C
C        FIND POINT WITH LOWEST FUNCTION VALUE
C
      KOUNT = 1
      IA = 0
      IF (IPRINT) 72,80,72
   72 WRITE(6,21)
   21 FORMAT(/,2X,'VALUES OF THE LEAST SQUARES FUNCTION')
```

```
      WRITE(6,22) (J,F(J),J=1,KN)
   22 FORMAT(/,3(2X,2HF(,I2,4H) = ,1PD13.6))
C
   80 IEV1 =1
      DO 100 ICM=2,KN
      IF (F(IEV1)-F(ICM)) 100,100,90
   90 IEV1 = ICM
  100 CONTINUE
C
C        FIND POINT WITH HIGHEST FUNCTION VALUE
C
      IEV2 = 1
      DO 120 ICM=2,KN
      IF (F(IEV2)-F(ICM)) 110,110,120
  110 IEV2 = ICM
  120 CONTINUE
      IF (F(IEV2)-(F(IEV1)+BETA)) 140,130,130
C
C        CHECK CONVERGENCE CRITERIA
C
  130 KOUNT = 1
      GO TO 150
  140 KOUNT = KOUNT + 1
      IF (KOUNT-GAMMA) 150,240,240
C
C        REPLACE POINT WITH LOWEST FUNCTION VALUE
C
  150 CALL CENTR (N,M,KN,IEV1,I,XC,X,K1)
C
      DO 160 JJ=1,N
  160 X(IEV1,JJ) = (1.0+ALPHA)*(XC(JJ))-ALPHA*(X(IEV1,JJ))
      I = IEV1
C
      CALL CHEK  (N,M,KN,X,G,H,I,KCODE,XC,DELTA,K1)
      CALL FUNK (N,M,KN,X,F,I,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1WL,WE,TS,X2)
C
C        REPLACE NEW POINT IF IT REPEATS AS LOWEST FUNCTION VALUE
C
      KASE = 1
  170 IEV2 = 1
      DO 190 ICM=2,KN
      IF (F(IEV2)-F(ICM)) 190,190,180
  180 IEV2 = ICM
  190 CONTINUE
C
      IF (IEV2-IEV1) 220,200,220
  200 DO 210 JJ=1,N
      X(IEV1,JJ) = (X(IEV1,JJ) + XC(JJ))/2.0
  210 CONTINUE
C
      I = IEV1
C
      CALL CHEK  (N,M,KN,X,G,H,I,KCODE,XC,DELTA,K1)
      CALL FUNK (N,M,KN,X,F,I,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1WL,WE,TS,X2)
C
      IF (KASE.EQ.40) GO TO 240
      KASE = KASE + 1
```

```
      GO TO 170
  220 CONTINUE
      IF (!PRINT) 230,228,230
  230 WRITE(6,23) IT
   23 FORMAT(//,2X,17HITERATION NUMBER ,I5)
      WRITE(6,24)
   24 FORMAT(/,2X,30HCOORDINATES OF CORRECTED POINT)
      WRITE(6,19) (IEV1,JC,X(IEV1,JC),JC=1,N)
      WRITE(6,21)
      WRITE(6,22) (I,F(I),I=1,KN)
      WRITE(6,25)
   25 FORMAT(/,2X,27HCOORDINATES OF THE CENTROID)
      WRITE(6,26) (JC,XC(JC),JC=1,N)
   26 FORMAT(/,3(2X,2HX(,I2,6H,C) = ,1PD14.6,4X))
  228 IT = IT + 1
      IF (IT-ITMAX) 80,80,240
C
  240 RETURN
      END



      SUBROUTINE CHEK  (N,M,KN,X,G,H,I,KCODE,XC,DELTA,K1)
      IMPLICIT REAL*8 (A-H,O-Z)
C
C        ARGUMENT LIST
C
C        ALL ARGUMENTS DEFINED IN MAIN LINE AND CONSX
C
      DIMENSION X(6,3),G(3),H(3),XC(3),DELTA(3)
C
   10 KT = 0
C
      CALL CONST (N,M,KN,X,G,H,I)
C
C        CHECK AGAINST EXPLICIT CONSTRAINTS
C
      DO 50 J=1,N
      IF (X(I,J)-G(J)) 20,20,30
   20 X(I,J) = G(J) + DELTA(J)
      GO TO 50
   30 IF (H(J)-X(I,J)) 40,40,50
   40 X(I,J) = H(J) - DELTA(J)
   50 CONTINUE
C
      IF (KCODE) 110,110,60
C
C        CHECK AGAINST THE IMPLICIT CONSTRAINTS
C
   60 NN = N + 1
      DO 100 J=NN,M
C
      CALL CONST (N,M,KN,X,G,H,I)
C
      IF (X(I,J)-G(J)) 30,70,70
   70 IF (H(J)-X(I,J)) 80,100,100
   80 IEV1 = I
      KT = 1
```

```
C
      CALL CENTR (N,M,KN,IEV1,I,XC,X,K1)
C
      DO 90 JJ=1,N
      X(I,JJ) = (X(I,JJ) + XC(JJ))/2.0
   90 CONTINUE
  100 CONTINUE
C
      IF (KT) 110,110,10
C
  110 RETURN
      END



      SUBROUTINE CENTR (N,M,KN,IEV1,I,XC,X,K1)
      IMPLICIT REAL*8 (A-H,O-Z)
C
      DIMENSION X(6,3),XC(3)
C
      DO 20 J=1,N
      XC(J) = 0.0
      DO 10 IL=1,K1
   10 XC(J) = XC(J) + X(IL,J)
      RK = K1
   20 XC(J) = (XC(J)-X(IEV1,J))/(RK-1.0)
C
      RETURN
      END



      SUBROUTINE FUNK (N,M,KN,X,F,I,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,
     1                 DENSS,QS,WL,WE,TE,X2)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MU,MUL,MUV,K,KL,KV
      DIMENSION X(6,3),F(6),WP(35),PBAR(35),PC(35),VL(35),DLC(35),
     1          VV(35),Z(35),DGC(35),T(200),Y(200),WE(35),WL(35),QS(35)
      COMMON/PROPTY/KU,KZ,DL,DV,HL,HV,S,SL,SV,CV,CVL,CVV,CP,CPL,CPV,
     1GAMMA,GAMMAL,GAMMAV,C,CL,CVP,MU,MUL,MUV,K,KL,KV,SIGMA,EXCESK,EXCL
     2,EXCV
C
C
C
      KU=3
      GO TO (1000,2000,3000),KCOND
C
C
C
C        IN THE COMPRESSED LIQUID REGION
C
C
C
 2000 KR=0
      CALL WASP (1,0,TI,X(I,1),D,H,KR)
      VLI=1.0/D
      V=X(I,2)*VLI/POR
```

```
C
      DO 30 L=1,JK
      WC=X(I,2)-WP(L)+WE(L)-WL(L)
      AA=WE(L)/X(I,2)
      BB=WP(L)/X(I,2)
      CC=WL(L)/X(I,2)
C
C        SOLVE REDUCED MASS-ENERGY BALANCE EQUATION
C
      VL(L)=VLI/(1.0+AA-BB-CC)
C
      X2=(((V*POR)/WC)-VL(L))/(-VL(L))
      DLC(L)=1.0/VL(L)
C
      KR=0
      CALL WASP (2,0,TC,P,DLC(L),H,KR)
   11 PC(L)=P
   30 CONTINUE
      GO TO 10
C
C
C
C        IN THE SUPERHEATED STEAM REGION
C
C
C
 3000 KR=0
      VVI=(10.73*TI)/(X(I,1)*18.0)
      V=X(I,2)*VVI/POR
C
      DO 51 L=1,JK
      WC=X(I,2)-WP(L)+WE(L)-WL(L)
      CALL WASP (1,0,TC,PBAR(L),D,H,KR)
      VV(L)=1.0/D
      Z(L)=(VV(L)*PBAR(L)*18.0)/(10.73*TC)
      AAA=WE(L)/X(I,2)
      BBB=WP(L)/X(I,2)
      CCC=WL(L)/X(I,2)
C
C        SOLVE REDUCED MASS-ENERGY BALANCE EQUATION
C
      PC(L)=X(I,1)*(1.0+AAA-BBB-CCC)*Z(L)
C
      PPX=PC(L)/Z(L)
      VVG=(10.73*TC)/(PPX*18.0)
      X2=(((V*POR)/WC)/VGG)
   51 CONTINUE
      GO TO 10
C
C
C
C        IN THE SATURATED LIQUID - STEAM REGION
C
C
C
 1000 KR=1
      PI=0.0
      CALL WASP (1,1,X(I,1),PI,D,H,KR)
C
```

```
      HFI=HL
      HGI=HV
      VFI=1.0/DL
      VGI=1.0/DV
C
      PE=0.0
      KR=1
      CALL WASP (1,1,TE,PE,D,H,KR)
      HE=HL
C
      SVOLI=VFI*(1.0-X(I,3))+VGI*X(I,3)
      V=X(I,2)*SVOLI/POR
      HI=HFI*(1.0-X(I,3))+HGI*X(I,3)
C
      DO 110 JJ=1,JK
C
      WC=X(I,2)+WE(JJ)-WP(JJ)-WL(JJ)
C
      KK=1
   75 T(1)=760.0
      T(2)=760.0
      T(3)=760.0
      DO 100 J=3,200
      HF=245.418777+(27.3585358*((T(J)-460.)/100.))+(5.24177074*(((T(J)
     1   -460.)/100.)**2))+(0.34823012*(((T(J)-460.)/100.)**3))-
     2   (344.718262/((T(J)-460.)/100.))
      HG=1021.10571+(16.3022919*((T(J)-460.)/100.))+(13.8019953*(((T(J)
     1   -460.)/100.)**2))-(2.18339539*(((T(J)-460.)/100.)**3))+
     2   (134.681641/((T(J)-460.)/100.))
      VF=0.01792239+(0.00215744*((T(J)-460.)/100.))-(0.00076399*(((T(J)
     1   -460.)/100.)**2))+(0.00009997*(((T(J)-460.)/100.)**3))-
     2   (0.00839130/((T(J)-460.)/100.))
      VG=DEXP(0.90465665-(0.49597612*((T(J)-460.)/100.))-(0.01500756*
     1   (((T(J)-460.)/100.)**2))+(7.75882149/((T(J)-460.)/100.)))
C
      X2=(((V*POR)/WC)-VF)/(VG-VF)
C
      SPHT=(1.3D-04)*(T(J)-460.)+0.33
C
      HC=(1.0-X2)*HF+X2*HG
      HP=HC
      HHL=HC
C
      GRP=DENSS*SPHT*(1.0-POR)
C
C
C        SOLVE MASS-ENERGY BALANCE EQUATION
C
C
      Y(J)=X(I,2)*HI+V*GRP*(X(I,1)-T(J))-WL(JJ)*HHL+WE(JJ)*HE-WP(JJ)*HP+
     1     QS(JJ)-WC*HC
C
C
      IF (Y(3).LE.0.0) GO TO 200
C
   80 GO TO (1,2,3,4,5,6,7),KK
    1 IF (Y(J).LE.0.0) GO TO 70
      IF (Y(J).GT.0.0) GO TO 50
   70 KK=KK+1
```

```
      GO TO 80
    2 T(J+1)=T(J-2)+1.0
      KK=KK+1
      GO TO 100
    3 IF (Y(J).LE.0.0) GO TO 90
      IF (Y(J).GT.0.0) GO TO 55
   55 T(J+1)=T(J)+1.0
      GO TO 100
   90 KK=KK+1
      GO TO 80
    4 T(J+1)=T(J-2)+0.1
      KK=KK+1
      GO TO 100
    5 IF (Y(J).LE.0.0) GO TO 66
      IF (Y(J).GT.0.0) GO TO 65
   65 T(J+1)=T(J)+0.1
      GO TO 100
   66 KK=KK+1
      GO TO 80
    6 T(J+1)=T(J-2)+0.01
      KK=KK+1
      GO TO 100
    7 IF (Y(J).LE.0.0) GO TO 200
      IF (Y(J).GT.0.0) GO TO 67
   67 T(J+1)=T(J)+0.01
      GO TO 100
   50 T(J+1)=T(J)+10.0
  100 CONTINUE
C
  200 T(JJ)=T(J)
      SPVOL=VF*(1.0-X2)+VG*X2
      DDD=1.0/SPVOL
      KR=0
      CALL WASP(2,0,T(JJ),PC(JJ),DDD,H,KR)
  110 CONTINUE
C
C
C        LEAST SQUARES VALUE , LST
C
C
   10 AST=0.0
      DO 40 M=1,JK
      AST=((PBAR(M)-PC(M))**2)+AST
   40 CONTINUE
      LST=AST
C
      F(I) = -LST
C
  999 RETURN
      END



      SUBROUTINE CONST (N,M,KN,X,G,H,I)
      IMPLICIT REAL*8 (A-H,O-Z)
C
      DIMENSION X(6,3),G(3),H(3)
C
```

```
C        VARY CONSTRAINTS UNTIL OPTIMUM IS FOUND
C
      G(1) =
      H(1) =
      G(2) =
      H(2) =
         .
         .
         .
      G(M) =
      H(M) =
      RETURN
      END
```

COMPLEX PROCEDURE OF BOX

PARAMETERS

N = 3 M = 3 KN = 6 ITMAX = 500 IC = 3

ALPHA = 1.30 BETA = 0.10000 GAMMA = 5

DELTA(1) = 1.00000-02 DELTA(2) = 1.00000 07 DELTA(3) = 1.00000-04

RANDOM NUMBERS

R(2, 1) = 0.2315 R(2, 2) = 0.0585 R(2, 3) = 0.7652

R(3, 1) = 0.9572 R(3, 2) = 0.1238 R(3, 3) = 0.5324

R(4, 1) = 0.3987 R(4, 2) = 0.5165 R(4, 3) = 0.9174

R(5, 1) = 0.7380 R(5, 2) = 0.2157 R(5, 3) = 0.0254

R(6, 1) = 0.0215 R(6, 2) = 0.8532 R(6, 3) = 0.1224

COORDINATES OF INITIAL COMPLEX

X(1, 1) = 9.3000000 02 X(1, 2) = 1.0000000 13 X(1, 3) = 9.9999960-02

X(2, 1) = 8.4630000 02 X(2, 2) = 1.3510000 12 X(2, 3) = 7.6520000-01

X(3, 1) = 9.9144000 02 X(3, 2) = 2.2428000 12 X(3, 3) = 5.3240000-01

X(4, 1) = 8.7974000 02 X(4, 2) = 4.5990000 12 X(4, 3) = 9.1040000-01

X(5, 1) = 9.5760000 02 X(5, 2) = 2.7942000 12 X(5, 3) = 2.5400000-02

X(6, 1) = 8.0430000 02 X(6, 2) = 6.6192000 12 X(6, 3) = 1.2240000-01

VALUES OF THE LEAST SQUARES FUNCTION

F(1) = -3.1778000 04 F(2) = -1.0141330 06 F(3) = -1.2759000 05
F(4) = -4.8215900 05 F(5) = -1.0403000 04 F(6) = -9.1224100 05

ITERATION NUMBER 10

COORDINATES OF CORRECTED POINT

X(4, 1) = 9.6341170 02 X(4, 2) = 5.1232090 12 X(4, 3) = 2.6965560-01

VALUES OF THE LEAST SQUARES FUNCTION

F(1) = -3.1778000 04 F(2) = -9.5760000 03 F(3) = -3.7812000 04
F(4) = -3.5672000 04 F(5) = -1.0403000 04 F(6) = -3.5980000 04

COORDINATES OF THE CENTROID

X(1,C) = 9.5448170 02 X(2,C) = 4.9205740 12 X(3,C) = 2.7315010-01

ITERATION NUMBER 20

COORDINATES OF CORRECTED POINT

X(2, 1) = 9.4252270 02 X(2, 2) = 4.9650410 12 X(2, 3) = 1.7060960-01

VALUES OF THE LEAST SQUARES FUNCTION

F(1) = -2.6430000 03 F(2) = -3.3450000 03 F(3) = -4.2900000 03
F(4) = -1.2860000 03 F(5) = -4.9950000 03 F(6) = -3.6640000 03

COORDINATES OF THE CENTROID

X(1,C) = 9.4451990 02 X(2,C) = 4.7262670 12 X(3,C) = 1.9496810-01

ITERATION NUMBER 30

COORDINATES OF CORRECTED POINT

X(4, 1) = 9.5089070 02 X(4, 2) = 2.7682550 12 X(4, 3) = 5.7574380-02

VALUES OF THE LEAST SQUARES FUNCTION

F(1) = -3.9600000 02 F(2) = -6.4000000 02 F(3) = -1.2500000 02
F(4) = -8.1810000 02 F(5) = -8.3400000 02 F(6) = -7.6700000 02

COORDINATES OF THE CENTROID

X(1,C) = 9.5006700 02 X(2,C) = 2.9494330 12 X(3,C) = 6.5785010-02

ITERATION NUMBER 40

COORDINATES OF CORRECTED POINT

X(1, 1) = 9.5108610 02 X(1, 2) = 2.0360250 12 X(1, 3) = 7.1231670-02

VALUES OF THE LEAST SQUARES FUNCTION

F(1) = -7.1000000 01 F(2) = -7.8000000 01 F(3) = -1.2600000 02
F(4) = -1.0200000 02 F(5) = -1.0700000 02 F(6) = -6.7000000 01

COORDINATES OF THE CENTROID

X(1,C) = 9.5195490 02 X(2,C) = 1.9005060 12 X(3,C) = 1.3044030-01

```
ITERATION NUMBER    50

COORDINATES OF CORRECTED POINT

X( 5, 1) =  9.5201550 02  X( 5, 2) =  1.9341740 12  X( 5, 3) =  7.0316330-02

VALUES OF THE LEAST SQUARES FUNCTION

F( 1) = -1.6000000 01  F( 2) = -4.9000000 01  F( 3) = -5.4000000 01
F( 4) = -4.8000000 01  F( 5) = -2.4000000 01  F( 6) = -3.0000000 01

COORDINATES OF THE CENTROID

X( 1,C) =   9.5194590 02      X( 2,C) =   1.9014710 12      X( 3,C) =   9.6258380-02



ITERATION NUMBER    60

COORDINATES OF CORRECTED POINT

X( 3, 1) =  9.5236340 02  X( 3, 2) =  1.8551370 12  X( 3, 3) =  6.4698450-02

VALUES OF THE LEAST SQUARES FUNCTION

F( 1) = -1.6000000 01  F( 2) = -1.8000000 01  F( 3) = -1.6000000 01
F( 4) = -1.9000000 01  F( 5) = -1.0000000 01  F( 6) = -1.2000000 01

COORDINATES OF THE CENTROID

X( 1,C) =   9.5236680 02      X( 2,C) =   1.8627160 12      X( 3,C) =   6.7364290-02



ITERATION NUMBER    70

COORDINATES OF CORRECTED POINT

X( 4, 1) =  9.5229470 02  X( 4, 2) =  1.8942990 12  X( 4, 3) =  7.8932040-02

VALUES OF THE LEAST SQUARES FUNCTION

F( 1) = -8.0000000 00  F( 2) = -1.3[illegible]0 01  F( 3) = -9.0000000 00
F( 4) = -1.0000000 01  F( 5) = -1.0000000 01  F( 6) = -8.0000000 00

COORDINATES OF THE CENTROID

X( 1,C) =   9.5246980 02      X( 2,C) =   1.8650540 12      X( 3,C) =   7.3167510-02
```

*** SATURATED LIQUID-STEAM RESERVOIR ***

FINAL LEAST SQUARES VALUE = -8.000000000 00

FINAL VALUES

INITIAL TEMPERATURE = 952.518912

INITIAL MASS = 1.875924090 12

INITIAL STEAM QUALITY = 0.078475

RESERVOIR PROPERTIES

POROSITY = 0.20000

ROCK DENSITY = 190.00000

INFLUX TEMPERATURE = 960.00000

ACTUAL PRESSURE	CALCULATED PRESSURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX
618.00000	615.99883	1.01800000 12	1.00000000 00	1.00000000 00	1.00000000 00
608.00000	608.64002	1.16000000 12	2.00000000 00	2.00000000 00	2.00000000 00
597.00000	599.00717	1.29100000 12	3.00000000 00	3.00000000 00	3.00000000 00
587.00000	587.02078	1.40300000 12	4.00000000 00	4.00000000 00	4.00000000 00

APPENDIX E

COMPUTER PROGRAM PRE

USER'S GUIDE, LISTING, AND PRINTOUT

PRE User's Guide

Program Description

1. Usage:

The computer program consists of a main program and three subroutines (FUNK, SST, and WASP). Reservoir characteristics and the optimum initial conditions from BOX are passed to SUBROUTINE FUNK from the main program. The final printout includes the matching and prediction information of the geothermal reservoir.

2. Subroutines Required:

SUBROUTINE FUNK (X,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS, QS,WL,WE,TE,KFT,JFT,JRATE,WPFT,IJK,PFT,WEFT,WLFT,X2,KCHK, KRATE,QSFT,WER,WLR,QSR,LST) matches and predicts (30 years) the performance of a compressed liquid, saturated liquid-steam, or superheated steam reservoir. Phase changes are also accounted for as explained in section IV.2.2. Description of Computer Program PRE.

SUBROUTINE SST (JK,PBAR,PC,LST) calculates the least squares value.

SUBROUTINE WASP (KS,KP,T,P,D,H,KR) calculates the thermodynamic properties of water and steam (User's Guide in Appendix F).

3. Description of Parameters:

PRE uses the following parameters that were described in BOX: KCOND,JK,WP,PBAR,TI,TC,WE,WL,QS,POR,DENSS,TE,VLI,V,WC, VL,X2,DLC,PC,VVI,VV,Z,PPX,VGG,HFI,HGI,VFI,VGI,HE,SVOLI,HI,

T( ),HF,HG,VF,VG,SPHT,HC,HE,HP,HHL,Y,SPVOL,DDD,LST,KS,KP,
T,P,D,H,KR.

Defined in main program

JFT — number of unit time (years, months, etc.) projection is made into the future (=30 years)

JRATE — number of different rates (KRATE) for future projection

KRATE — production rate for performance projection

WER — influx rate for future projection

WLR — loss rate for future projection

QSR — net heat conducted rate for future projection

WPFT — cumulative mass produced in future projection

WEFT — cumulative mass influx in future projection

WLFT — cumulative mass loss in future projection

QSFT — cumulative net heat conducted in future projection

* the preceding parameters are user supplied

KFT — program controller

=1 uses mass-energy-volumetric balance equations to match actual performance data

=2 uses mass-energy-volumetric balance equations for future projections

KCHK — program controller

=1 print reservoir condition values

≠1 does not print reservoir condition values

Defined in SUBROUTINE FUNK

X2I initial steam quality

PZZ current (pressure/compressibility factor)

PZ current (pressure/compressibility factor) in future projection

DGC current vapor density in future projection

NTRA program controller

=0 future projection calculation

=1 transition point location (two-phase to superheated steam)

SPFT current fluid specific volume in future projection

DFT current fluid density in future projection

W current reservoir temperature in future projection

* in the location of transition point (compressed liquid to two-phase)

WWI cumulative mass produced

WWE cumulative mass influx

WWL cumulative mass loss

WWC current mass

VVI current liquid specific volume

DDI current liquid density

WWII cumulative mass produced at transition point

XXX fractional location of transition point in unit time interval

SSVV current fluid specific volume at transition point
* in future projection from phase change (two-phase to superheated steam)

WTP cumulative mass produced

WTE cumulative mass influx

WTL cumulative mass loss

QTS cumulative net heat conducted into reservoir

PPZZ current (pressure/compressibility factor)

VVZZ current vapor specific volume

DTT current vapor density

* in the future projection from phase change (compressed liquid to two-phase)

WWPP cumulative mass produced

WWEE cumulative mass influx

WWLL cumulative mass loss

QQSS cumulative net heat conducted into reservoir
* in the location of transition point (two-phase to superheated steam or compressed liquid to two-phase to superheated steam)

SPTZ current fluid specific volume

DTZ current fluid density

WZ current reservoir temperature

PTZ current pressure

WWTP cumulative mass produced

WWTE cumulative mass influx

WWTL cumulative mass loss

QQTS cumulative net heat conducted into reservoir

WWTC current mass

VTZ current fluid specific volume at transition point

ZZ current (pressure/compressibility factor) at transition point

WWTT cumulative mass produced at transition point

YYY fractional location of transition point in unit time interval

Defined in SUBROUTINE SST

Parameters defined in Appendix D

Defined in SUBROUTINE WASP

Parameters defined in Appendix F

4. DIMENSION Requirements:

The DIMENSION statements in the main program and SUBROUTINE FUNK can be modified to the requirements of a particular problem. The parameters in the following DIMENSION statement conform to the input parameters definitions above.

```
DIMENSION X(3),WP(JK),PBAR(JK),WL(JK),WEFT(JFT),WLFT(JFT),
  QS(JK),PC(JK),WPFT(JRATE,JFT),PFT(JFT),KRATE(JRATE),
  WE(JK),QSFT(JFT),VL(JK),DLC(JK),VV(JK),Z(JK),DGC(JK),
  T(200),Y(200),PZ(JFT),W(JFT),WWI(200),WWPP(JFT),WWEE(JFT)
  ,WWLL(JFT),WTP(JFT),WZ(200),WTE(JFT),WTL(JFT),WWE(200),
  WWL(200),WWTE(200),WWTL(200),QQSS(JFT),QQTS(200),QTS(JFT)
  ,WWTP(200),WWC(200),WWTC(200),PTZ(200)
```

5. Input Format:

Initialize optimum initial conditions determined by BOX in beginning of main program as follows: if

KCOND = 1 (saturated liquid-steam)

X(1) = initial temperature

X(2) = initial mass

X(3) = initial steam quality

KCOND = 2 (compressed liquid)

X(1) = initial pressure

X(2) = initial mass

KCOND = 3 (superheated steam)

X(1) = initial (pressure/compressibility factor)

X(2) = initial mass

CARD TYPE	FORMAT	CONTENTS
1	4I5	KCOND,JK,JFT,JRATE
2	5D16.8	(WP(MM),MM=1,JK)
3	8F10.4	(PBAR(NN),NN=1,JK)
4	2F10.4	TI,TC
if KCOND=1, set TI=TC=0.0		
5	8D10.4	(WE(L),L=1,JK)
6	8D10.4	(WL(L),L=1,JK)
7	8D10.4	(QS(L),L=1,JK)
8	5D16.8	(KRATE(I),I=1,JRATE)
9	3D10.4	WER,WLR,QSR

CARD TYPE	FORMAT	CONTENTS
10	3F10.4	POR,DENSS,TE

6. Output:

The main program writes the performance matching data along with the thirty-year projections at various production flow rates. The performance matching printout consists of the control parameters, the final optimum values, the reservoir properties, and the listing of actual pressure, calculated pressure, mass produced, mass influx, mass loss, heat influx, and steam quality. The performance projection printout includes the mass production rate and a listing identical to the matching printout, excluding the actual pressure.

In the event a phase change occurs, mass produced, mass loss, and heat influx will have two lines of information for every projection entry. The first line represents values with the transition point as the initial condition; the second line is the continuation of values from the previous phase (i.e. old initial condition). The predictions stop if the pressure is less than 60 psia, the current mass is less than zero, or the thirty-year projection is complete.

7. Summary of User Requirements:

a. Initialize the optimum initial parameters determined by BOX as specified in the Input Format.

b. Determine values for KCOND,JK,JFT,JRATE,KRATE,WER,WLR, and QSR.

c. Read production data: WP,PBAR,TI,TC,WE,WL,QS and reservoir properties: POR,DENSS,TE. Parameter units must be expressed as shown in Table 26, KU=3.

d. Adjust DIMENSION and FORMAT statements as necessary, if projections beyond thirty years are desired or greater accuracy is needed.

```
C
C
C
C       PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR USING
C
C                   THE MASS-ENERGY BALANCE EQUATIONS
C
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 KRATE
      DIMENSION X(3),WP(35),PBAR(35),WL(35),WEFT(35),WLFT(35),QS(35),
     1          PC(35),QSFT(35),WPFT(10,35),PFT(35),KRATE(10),WE(35)
C
C
C       KCOND(=KR) = 1 SATURATED LIQUID AND STEAM REGION
C
C                          X(1) = INITIAL TEMPERATURE
C                          X(2) = INITIAL MASS
C                          X(3) = INITIAL STEAM QUALITY
C
C                  = 2 COMPRESSED LIQUID REGION
C
C                          X(1) = INITIAL PRESSURE
C                          X(2) = INITIAL MASS
C
C                  = 3 SUPERHEATED STEAM REGION
C
C                          X(1) = INITIAL (PRESSURE/COMPRESSIBILITY FACTOR)
C                          X(2) = INITIAL MASS
C
C
C       OPTIMUM INITIAL PARAMETERS DETERMINED FROM - BOX
C
      X(1) =
      X(2) =
        .
        .
        .
      X(N) =
C
C
C
      READ(5,1) KCOND,JK,JFT,JRATE
    1 FORMAT(4I5)
      READ(5,5) (WP(MM),MM=1,JK)
    5 FORMAT(5D16.8)
      READ(5,6) (PBAR(NN),NN=1,JK)
    6 FORMAT(8F10.4)
      READ(5,926) TI,TC
  926 FORMAT(2F10.4)
      READ(5,927) (WE(L),L=1,JK)
      READ(5,927) (WL(L),L=1,JK)
      READ(5,927) (QS(L),L=1,JK)
  927 FORMAT(8D10.4)
      READ(5,955) (KRATE(I),I=1,JRATE)
  955 FORMAT(5D16.8)
      READ(5,956) WEP,WLP,QSP
  956 FORMAT(3D10.4)
```

```
      READ(5,928) POR,DENSS,TE
  928 FORMAT(3F10.4)
C
      DO 351 I=1,JRATE
      WPFT(I,1)=WP(JK)
      DO 353 J=1,JFT
      WPFT(I,J+1)=WPFT(I,J)+KRATE(I)
  353 CONTINUE
  351 CONTINUE
C
      WEFT(1)=WE(JK)
      WLFT(1)=WL(JK)
      QSFT(1)=QS(JK)
      DO 352 I=1,JFT
      WEFT(I+1)=WEFT(I)+WER
      WLFT(I+1)=WLFT(I)+WLR
      QSFT(I+1)=QSFT(I)+QSR
  352 CONTINUE
C
      WRITE(6,150) KCOND,JK,JFT,JRATE
  150 FORMAT(/,2X,'KCOND = ',I2,3X,'JK = ',I2,3X,'JFT = ',I2,3X,'JRATE =
     1 ',I2)
   20 GO TO (110,120,130),KCOND
  110 WRITE(6,945)
  945 FORMAT('1',////,6X,'*** SATURATED LIQUID-STEAM RESERVOIR ***')
      GO TO 135
  120 WRITE(6,946)
  946 FORMAT('1',////,6X,'*** COMPRESSED LIQUID RESERVOIR ***')
      GO TO 135
  130 WRITE(6,947)
  947 FORMAT('1',////,6X,'*** SUPERHEATED STEAM RESERVOIR ***')
C
  135 WRITE(6,15)
   15 FORMAT(///,14X,'FINAL VALUES')
      KFT=1
      KCHK=2
      CALL FUNK (X,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1           WL,WE,TE,KFT,JFT,JRATE,WPFT,IJK,PFT,WEFT,WLFT,X2,KCHK,
     2           KRATE,QSFT,WER,WLR,QSR,LST)
      WRITE(6,14) LST
   14 FORMAT(/,6X,'LEAST SQUARES = ',I5)
C
      GO TO (22,23,24),KCOND
C
   22 WRITE(6,940) X(1)
  940 FORMAT(/,6X,'INITIAL TEMPERATURE = ',F13.6)
      WRITE(6,931) X(2)
  931 FORMAT(/,6X,'INITIAL MASS = ',1PD15.8)
      WRITE(6,932) X(3)
  932 FORMAT(/,6X,'INITIAL STEAM QUALITY = ',F13.6)
      GO TO 25
C
   23 WRITE(6,933) X(1)
  933 FORMAT(/,6X,'INITIAL PRESSURE = ',F13.6)
      WRITE(6,931) X(2)
      WRITE(6,934) TI
  934 FORMAT(/,6X,'INITIAL TEMPERATURE = ',F13.5)
      GO TO 25
C
```

```
   24 WRITE(6,943) X(1)
  943 FORMAT(/,6X,'INITIAL (PRESSURE/COMPRESSIBILITY FACTOR) = ',F13.6)
      WRITE(6,931) X(2)
      WRITE(6,934) TI
C
   25 WRITE(6,159)
  159 FORMAT(///,10X,'RESERVOIR PROPERTIES')
      WRITE(6,160) POR
  160 FORMAT(/,6X,'POROSITY = ',F13.5)
      WRITE(6,162) DENSS
  162 FORMAT(/,6X,'ROCK DENSITY = ',F13.5)
      WRITE(6,166) TE
  166 FORMAT(/,6X,'INFLUX TEMPERATURE = ',F13.5)
C
      WRITE(6,190)
  190 FORMAT(///,12X,'ACTUAL',5X,'CALCULATED',7X,'CURRENT',10X,'MASS',13
     1X,'MASS',13X,'MASS',13X,'HEAT',11X,'STEAM')
      WRITE(6,191)
  191 FORMAT(6X,'KR',3X,'PRESSURE',5X,'PRESSURE',6X,'TEMPERATURE',6X,
     1 'PRODUCED',10X,'INFLUX',12X,'LOST',12X,'INFLUX',9X,'QUALITY')
C
  210 KCHK=1
      KFT=1
      CALL FUNK (X,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1           WL,WE,TE,KFT,JFT,JRATE,WPFT,IJK,PFT,WEFT,WLFT,X2,KCHK,
     2           KRATE,QSFT,WER,WLR,QSR,LST)
C
      KFT=KFT+1
      DO 360 IJK=1,JRATE
      WRITE(6,949)
  949 FORMAT('1',////,6X,'*** FUTURE PERFORMANCE PREDICTION OF A GEOTHER
     2MAL RESERVOIR ***')
      WRITE(6,957) KRATE(IJK)
  957 FORMAT(///,6X,'MASS PRODUCTION RATE,LBS/UNIT TIME = ',1PD15.8)
      WRITE(6,192)
  192 FORMAT(//,10X,'CALCULATED',7X,'CURRENT',10X,'MASS',13X,'MASS',13X,
     1'MASS',13X,'HEAT',11X,'STEAM')
      WRITE(6,193)
  193 FORMAT(6X,'KR',3X,'PRESSURE',6X,'TEMPERATURE',6X,'PRODUCED',10X,
     1'INFLUX',12X,'LOST',12X,'INFLUX',9X,'QUALITY')
C
      CALL FUNK (X,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,DENSS,QS,
     1           WL,WE,TE,KFT,JFT,JRATE,WPFT,IJK,PFT,WEFT,WLFT,X2,KCHK,
     2           KRATE,QSFT,WER,WLR,QSR,LST)
C
  360 CONTINUE
C
      GO TO 999
C
C
  999 STOP
      END



      SUBROUTINE FUNK (X,WP,PBAR,PC,KR,KCOND,JK,TI,TC,POR,
     1                 DENSS,QS,WL,WE,TE,KFT,JFT,JRATE,WPFT,IJK,PFT,
     2                 WEFT,WLFT,X2,KCHK,KRATE,QSFT,WER,WLR,QSR,LST)
```

```
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MU,MUL,MUV,K,KL,KV
      REAL*8 KRATE
      DIMENSION X(3),WP(35),PBAR(35),PC(35),VL(35),DLC(35),
     1          VV(35),Z(35),DGC(35),T(200),Y(200),WPFT(10,35),PFT(35),
     2          PZ(35),WE(35),WL(35),WEFT(35),WLFT(35),W(35),WWI(200)
     3          ,KRATE(10),WWPP(35),WWEE(35),WWLL(35),WTP(35),WZ(200),
     4          WTE(35),WTL(35),WWE(200),WWL(200),WWTE(200),WWTL(200)
     5          ,QS(35),QSFT(35),QQSS(35),QQTS(200),QTS(35),WWTP(200)
     6          ,WWC(200),WWTC(200),PTZ(200)
      COMMON/PROPTY/KU,KZ,DL,DV,HL,HV,S,SL,SV,CV,CVL,CVV,CP,CPL,CPV,
     1GAMMA,GAMMAL,GAMMAV,C,CL,CVP,MU,MUL,MUV,K,KL,KV,SIGMA,EXCESK,EXCL
     2,EXCV
C
      KU=3
      GO TO (1000,2000,3000),KCOND
C
C
C
C        IN THE COMPRESSED LIQUID REGION
C
C       FIND THE OPTIMUM INITIAL CONDITIONS
C
C
C
 2000 KR=0
      CALL WASP (1,0,TI,X(1),D,H,KR)
      VLI=1.0/D
      V=X(2)*VLI/POR
C
      GO TO (20,21),KFT
C
   20 ITE=1
      DO 30 L=1,JK
      WC=X(2)-WP(L)-WL(L)+WE(L)
      AA=WE(L)/X(2)
      BB=WP(L)/X(2)
      CC=WL(L)/X(2)
C
C        REDUCED MASS-ENERGY BALANCE EQUATION
C
      VL(L)=VLI/(1.0+AA-BB-CC)
C
      X2=(((V*POR)/WC)-VL(L))/(-VL(L))
      DLC(L)=1.0/VL(L)
      KR=0
      CALL WASP (2,0,TC,PC(L),DLC(L),H,KR)
      IF (KCHK.EQ.1) GO TO 420
      IF (KCHK.NE.1) GO TO 30
  420 IF (ITE.EQ.2) GO TO 400
C
C        CHECK FOR PHASE CHANGE
C
      IF (KR.EQ.2) GO TO 400
      IF (KR.EQ.1) GO TO 405
  405 WRITE(6,410)
  410 FORMAT(/,35X,'*** IN THE TWO-PHASE REGION ***')
      ITE=ITE+1
  400 WRITE(6,425) L,KR,PBAR(L),PC(L),TC,WP(L),WE(L),WL(L),QS(L),X2
```

```
  425 FORMAT(/,2X,I3,1X,I2,1X,F10.4,3X,F10.4,5X,F11.5,2X,1PD15.6,2X,D15.
     16,2X,D15.6,2X,D15.6,0PF13.5)
   30 CONTINUE
      GO TO 10
C
C
C        PERFORMANCE PREDICTION USING THE OPTIMUM INITIAL CONDITIONS
C
C
C
   21 L = 1
   31 WC=X(2)-WPFT(IJK,L)-WLFT(L)+WEFT(L)
      IF (WC.LT.0.0) GO TO 96
      AA=WEFT(L)/X(2)
      BB=WPFT(IJK,L)/X(2)
      CC=WLFT(L)/X(2)
C
C        REDUCED MASS-ENERGY BALANCE EQUATION
C
      VL(L)=VLI/(1.0+AA-BB-CC)
C
      X2=(((V*POR)/WC)-VL(L))/(-VL(L))
      DLC(L)=1.0/VL(L)
      KR=0
      CALL WASP(2,0,TC,PFT(L),DLC(L),H,KR)
      IF (KR.EQ.2) GO TO 315
      IF (KR.EQ.1) GO TO 305
  305 WRITE(6,310)
  310 FORMAT(/,35X,'*** IN THE TWO-PHASE REGION ***')
C
C        PHASE CHANGE - COMPRESSED LIQUID TO TWO PHASE
C
C        LOCATE THE TRANSITION POINT
C
      LL=L
      WWI(1)=WPFT(IJK,L-1)
      WWI(2)=WPFT(IJK,L-1)
      WWE(1)=WEFT(L-1)
      WWE(2)=WEFT(L-1)
      WWL(1)=WLFT(L-1)
      WWL(2)=WLFT(L-1)
C
      DO 2100 MA=2,200
      WWC(MA)=X(2)-WWI(MA)+WWE(MA)-WWL(MA)
      IF (WWC(MA).LT.0.0) GO TO 96
      AI=WWE(MA)/X(2)
      BI=WWI(MA)/X(2)
      CI=WWL(MA)/X(2)
      VVI=VLI/(1.0+AI-BI-CI)
      XX2=(((V*POR)/WWC(MA))-VVI)/(-VVI)
      DDI=1.0/VVI
      KR=0
      CALL WASP(2,0,TC,PPI,DDI,H,KR)
C
C        CHECK FOR PHASE CHANGE
C
 1100 IF (KR.EQ.2) GO TO 1101
      IF (KR.EQ.1) GO TO 1115
C
C        ITERATE BY 0.001
```

```
C
 1101 WWI(MA+1)=WWI(MA)*(1.0+0.001)
      WWE(MA+1)=WWE(MA)*(1.0+0.001)
      WWL(MA+1)=WWL(MA)*(1.0+0.001)
 2100 CONTINUE
C
C         CURRENT MASS @ TRANSITION POINT, WWII
C
 1115 WWII=WWC(MA)
      XXX=(WPFT(IJK,L)-WWI(MA))/(WPFT(IJK,L)-WPFT(IJK,L-1))
      X2I=0.0
      PI=0.0
      KR=1
      CALL WASP(1,1,TI,PI,D,H,KR)
      HFI=HL
      HGI=HV
      VFI=1.0/DL
      VGI=1.0/DV
C
      PE=0.0
      KR=1
      CALL WASP(1,1,TE,PE,D,H,KR)
      HE=HL
C
      HI=HFI*(1.0-X2I)+HGI*X2I
      SSVV=VFI*(1.0-X2I)+VGI*X2I
      GO TO 771
C
  315 WRITE(6,800) L,KR,PFT(L),TC,WPFT(IJK,L),WEFT(L),WLFT(L),QSFT(L),X2
  800 FORMAT(/,2X,I3,1X,I2,1X,F10.4,5X,F11.5,2X,1PD15.6,2X,D15.6,2X,D15.
     16,2X,D15.6,0PF13.5)
      IF (PFT(L).LT.60.0) GO TO 98
      IF (L.EQ.JFT) GO TO 999
      IF (L.NE.JFT) GO TO 210
  210 L = L + 1
      GO TO 31
C
C
C
C         IN THE SUPERHEATED STEAM REGION
C
C       FIND THE OPTIMUM INITIAL CONDITIONS
C
C
C
 3000 X2I=0.0
      VVI=(10.73*TI)/(X(1)*18.0)
      V=X(2)*VVI/POR
      GO TO (33,34),KFT
C
   33 DO 51 L=1,JK
      WC=X(2)-WP(L)-WL(L)+WE(L)
      KR=0
      CALL WASP (1,0,TC,PBAR(L),D,H,KR)
      VV(L)=1.0/D
C
C         REAL GAS LAW EQUATION
C
      Z(L)=(VV(L)*PBAR(L)*18.0)/(10.73*TC)
```

```
      AAA=WE(L)/X(2)
      BBB=WP(L)/X(2)
      CCC=WL(L)/X(2)
C
C        REDUCED MASS-ENERGY BALANCE EQUATION
C
      PC(L)=X(1)*(1.0+AAA-BBB-CCC)*Z(L)
C
      PZZ=PC(L)/Z(L)
      VGG=(10.73*TC)/(PZZ*18.0)
      X2=(((V*POR)/WC)/VGG)
      IF (KCHK.EQ.1) GO TO 426
      IF (KCHK.NE.1) GO TO 51
  426 WRITE(6,425) L,KR,PBAR(L),PC(L),TC,WP(L),WE(L),WL(L),QS(L),X2
   51 CONTINUE
      GO TO 10
C
C
C        PERFORMANCE PREDICTION USING THE OPTIMUM INITIAL CONDITIONS
C
C
   34 L = 1
   41 IF (KCOND.EQ.3) GO TO 758
      IF (KCOND.EQ.1) GO TO 759
C
  758 WC=X(2)-WPFT(IJK,L)-WLFT(L)+WEFT(L)
      IF (WC.LT.0.0) GO TO 96
      AAA=WEFT(L)/X(2)
      BBB=WPFT(IJK,L)/X(2)
      CCC=WLFT(L)/X(2)
C
C        REDUCED MASS-ENERGY BALANCE EQUATION
C
      PZ(L)=X(1)*(1.0+AAA-BBB-CCC)
C
      VV(L)=(10.73*TC)/(PZ(L)*18.0)
      X2=(((V*POR)/WC)/VV(L))
      DGC(L)=1.0/VV(L)
      KR=0
      CALL WASP(2,0,TC,PFT(L),DGC(L),H,KR)
      WRITE(6,800) L,KR,PFT(L),TC,WPFT(IJK,L),WEFT(L),WLFT(L),QSFT(L),X2
      IF (PFT(L).LT.60.0) GO TO 98
      IF (L.EQ.JFT) GO TO 999
      IF (L.NE.JFT) GO TO 215
  215 L = L + 1
      GO TO 758
C
C        PHASE CHANGE - TWO PHASE TO SUPERHEATED STEAM
C
  759 V=WWTT*VTZ/POR
      WTP(L)=KRATE(IJK)*YYY
      WTE(L)=WER*YYY
      WTL(L)=WLR*YYY
      QTS(L)=QSR*YYY
C
  761 WC=WWTT-WTP(L)+WTE(L)-WTL(L)
      IF (WC.LT.0.0) GO TO 96
      AJ=WTE(L)/WWTT
      BJ=WTP(L)/WWTT
```

```
      CJ=WTL(L)/WWTT
C
C        REDUCED MASS-ENERGY BALANCE EQUATION
C
      PPZZ=ZZ*(1.0+AJ-BJ-CJ)
C
      VVZZ=(10.73*TC)/(PPZZ*18.0)
      X2=(((V*POR)/WC)/VVZZ)
      DTT=1.0/VVZZ
      KR=0
      CALL WASP(2,J,TC,PFT(L),DTT,H,KR)
      WRITE(6,800) L,KR,PFT(L),TC,WTP(L),WTE(L),WTL(L),QTS(L),X2
      WRITE(6,813) WPFT(IJK,L),WEFT(L),WLFT(L),QSFT(L)
  813 FORMAT(37X,1PD15.6,2X,D15.6,2X,D15.6,2X,D15.6)
      IF (PFT(L).LT.60.0) GO TO 98
C
      IF (L.EQ.JFT) GO TO 999
      IF (L.NE.JFT) GO TO 760
  760 WTP(L+1)=WTP(L)+KRATE(IJK)
      WTE(L+1)=WTE(L)+WER
      WTL(L+1)=WTL(L)+WLR
      QTS(L+1)=QTS(L)+QSR
      L = L + 1
      GO TO 761
C
C
C
C        IN THE SATURATED LIQUID - STEAM REGION
C
C         FIND THE OPTIMUM INITIAL CONDITIONS
C
C
C
 1000 KR=1
      PI=0.0
      CALL WASP (1,1,X(1),PI,D,H,KR)
C
      HFI=HL
      HGI=HV
      VFI=1.0/DL
      VGI=1.0/DV
C
      PE=0.0
      KR=1
      CALL WASP (1,1,TE,PE,D,H,KR)
      HE=HL
C
      SVOLI=VFI*(1.0-X(3))+VGI*X(3)
      V=X(2)*SVOLI/POR
      HI=HFI*(1.0-X(3))+HGI*X(3)
C
      GO TO (79,81),KFT
C
   79 ITE=1
      DO 110 JJ=1,JK
      WC=X(2)+WE(JJ)-WP(JJ)-WL(JJ)
C
      KK=1
      T(1)=760.0
```

```
      T(2)=760.0
      T(3)=760.0
C
      DO 100 J=3,200
      HF=245.418777+(27.3585358*((T(J)-460.)/100.))+(5.24177074*(((T(J)
     1   -460.)/100.)**2))+(0.34823012*(((T(J)-460.)/100.)**3))-
     2   (344.718262/((T(J)-460.)/100.))
      HG=1021.10571+(16.3022919*((T(J)-460.)/100.))+(13.8019953*(((T(J)
     1   -460.)/100.)**2))-(2.18339539*(((T(J)-460.)/100.)**3))+
     2   (134.681641/((T(J)-460.)/100.))
      VF=0.01792239+(0.00215744*((T(J)-460.)/100.))-(0.00076399*(((T(J)
     1   -460.)/100.)**2))+(0.00009997*(((T(J)-460.)/100.)**3))-
     2   (0.00839130/((T(J)-460.)/100.))
      VG=DEXP(0.90465665-(0.49597612*((T(J)-460.)/100.))-(0.01500756*
     1   (((T(J)-460.)/100.)**2))+(7.75882149/((T(J)-460.)/100.)))
C
      X2=(((V*POR)/WC)-VF)/(VG-VF)
      SPHT=(1.3D-04)*(T(J)-460.)+0.33
      HC=(1.0-X2)*HF+X2*HG
      HP=HC
      HHL=HC
      GRP=DENSS*SPHT*(1.0-POR)
C
C        MASS-ENERGY BALANCE EQUATION
C
C
      Y(J)=X(2)*HI+V*GRP*(X(1)-T(J))-WL(JJ)*HHL+WE(JJ)*HE-WP(JJ)*HP+
     1     QS(JJ)-WC*HC
C
C
C        FIND THE CURRENT TEMPERATURE THAT EQUATES THE
C           MASS-ENERGY BALANCE EQUATION TO ZERO
C
      IF (Y(3).LE.0.0) GO TO 200
   80 GO TO (1,2,3,4,5,6,7),KK
C
    1 IF (T(J).GT.1165.4) GO TO 445
      IF (Y(J).LE.0.0) GO TO 70
      IF (Y(J).GT.0.0) GO TO 50
   70 KK=KK+1
      GO TO 80
    2 T(J+1)=T(J-2)+1.0
      KK=KK+1
      GO TO 100
    3 IF (T(J).GT.1165.4) GO TO 445
      IF (Y(J).LE.0.0) GO TO 90
      IF (Y(J).GT.0.0) GO TO 55
   55 T(J+1)=T(J)+1.0
      GO TO 100
   90 KK=KK+1
      GO TO 80
    4 T(J+1)=T(J-2)+0.1
      KK=KK+1
      GO TO 100
    5 IF (T(J).GT.1165.4) GO TO 445
      IF (Y(J).LE.0.0) GO TO 66
      IF (Y(J).GT.0.0) GO TO 65
   65 T(J+1)=T(J)+0.1
      GO TO 100
```

```
   66 KK=KK+1
      GO TO 80
    6 T(J+1)=T(J-2)+0.01
      KK=KK+1
      GO TO 100
    7 IF (T(J).GT.1165.4) GO TO 445
      IF (Y(J).LE.0.0) GO TO 200
      IF (Y(J).GT.0.0) GO TO 67
   67 T(J+1)=T(J)+0.01
      GO TO 100
   50 T(J+1)=T(J)+10.0
  100 CONTINUE
C
  200 SPVOL=VF*(1.0-X2)+VG*X2
      DDD=1.0/SPVOL
      T(JJ)=T(J)
C
      KR=0
      CALL WASP(2,0,T(JJ),PC(JJ),DDD,H,KR)
      IF (KCHK.EQ.1) GO TO 450
      IF (KCHK.NE.1) GO TO 110
  450 IF (ITE.EQ.2) GO TO 440
C
C        CHECK FOR PHASE CHANGE
C
      IF (KR.EQ.1) GO TO 440
      IF (KR.EQ.3) GO TO 445
  445 WRITE(6,446)
  446 FORMAT(/,35X,'*** IN THE SUPERHEATED STEAM REGION ***')
      ITE=ITE+1
  440 WRITE(6,425) JJ,KR,PBAR(JJ),PC(JJ),T(JJ),WP(JJ),WE(JJ),WL(JJ),QS(J
     1J),X2
  110 CONTINUE
      GO TO 10
C
C
C        PERFORMANCE PREDICTION USING THE OPTIMUM INITIAL CONDITIONS
C
C
   81 LL = 1
  771 NTRA=0
      GO TO (111,113),KCOND
  111 WC=X(2)+WEFT(LL)-WPFT(IJK,LL)-WLFT(LL)
      IF (WC.LT.0.0) GO TO 96
      GO TO 772
C
  113 V=WWII*SSVV/POR
      WWPP(LL)=KRATE(IJK)*XXX
      WWEE(LL)=WER*XXX
      WWLL(LL)=WLR*XXX
      QQSS(LL)=QSR*XXX
C
  114 WC=WWII+WWEE(LL)-WWPP(LL)-WWLL(LL)
      IF (WC.LT.0.0) GO TO 96
C
  772 KK=1
      T(1)=760.0
      T(2)=760.0
      T(3)=760.0
```

```
      DO 101 J=3,200
C
      HF=245.418777+(27.3585358*((T(J)-460.)/100.))+(5.24177074*(((T(J)
     1   -460.)/100.)**2))+(0.34823012*(((T(J)-460.)/100.)**3))-
     2   (344.718262/((T(J)-460.)/100.))
      HG=1021.10571+(16.3022919*((T(J)-460.)/100.))+(13.8019953*(((T(J)
     1   -460.)/100.)**2))-(2.18339539*(((T(J)-460.)/100.)**3))+
     2   (134.681641/((T(J)-460.)/100.))
      VF=0.01792239+(0.00215744*((T(J)-460.)/100.))-(0.00076399*(((T(J)
     1   -460.)/100.)**2))+(0.00009997*(((T(J)-460.)/100.)**3))-
     2   (0.00839130/((T(J)-460.)/100.))
      VG=EXP(0.90465665-(0.49597612*((T(J)-460.)/100.))-(0.01500756*
     1   (((T(J)-460.)/100.)**2))+(7.75882149/((T(J)-460.)/100.)))
C
      IF (NTRA.EQ.0) GO TO 92
      IF (NTRA.EQ.1) GO TO 94
   92 X2=(((V*POR)/WC)-VF)/(VG-VF)
      GO TO 95
   94 X2=(((V*POR)/WWTC(JZ))-VF)/(VG-VF)
   95 SPHT=(1.3D-04)*(T(J)-460.)+0.33
      HC=(1.0-X2)*HF+X2*HG
      HP=HC
      HHL=HC
      GRP=DENSS*SPHT*(1.0-POR)
C
      IF (NTRA.EQ.0) GO TO 743
      IF (NTRA.EQ.1) GO TO 744
  743 IF (KCOND.EQ.1) GO TO 745
      IF (KCOND.EQ.2) GO TO 746
C
C        MASS-ENERGY BALANCE EQUATION
C
C
  744 Y(J)=X(2)*HI+V*GRP*(X(1)-T(J))-WWTL(JZ)*HHL+WWTE(JZ)*HE-
     1      WWTP(JZ)*HP+QQTS(JZ)-WWTC(JZ)*HC
      GO TO 747
C
  745 Y(J)=X(2)*HI+V*GRP*(X(1)-T(J))-WLFT(LL)*HHL+WEFT(LL)*HE-
     1      WPFT(IJK,LL)*HP+QSFT(LL)-WC*HC
      GO TO 747
C
  746 Y(J)=WWII*HI+V*GRP*(TI-T(J))-WWLL(LL)*HHL+WWEE(LL)*HE-
     1      WWPP(LL)*HP+QQSS(LL)-WC*HC
C
C
C        FIND THE CURRENT TEMPERATURE THAT EQUATES THE
C           MASS-ENERGY BALANCE EQUATION TO ZERO
C
  747 IF (Y(3).LE.0.0) GO TO 201
  810 GO TO (11,12,13,14,15,16,17),KK
   11 IF (T(J).GT.1165.4) GO TO 325
      IF (Y(J).LE.0.0) GO TO 700
      IF (Y(J).GT.0.0) GO TO 705
  700 KK=KK+1
      GO TO 810
   12 T(J+1)=T(J-2)+1.0
      KK=KK+1
      GO TO 101
   13 IF (T(J).GT.1165.4) GO TO 325
```

```
      IF (Y(J).LE.0.0) GO TO 710
      IF (Y(J).GT.0.0) GO TO 720
  720 T(J+1)=T(J)+1.0
      GO TO 101
  710 KK=KK+1
      GO TO 810
   14 T(J+1)=T(J-2)+0.1
      KK=KK+1
      GO TO 101
   15 IF (T(J).GT.1165.4) GO TO 325
      IF (Y(J).LE.0.0) GO TO 731
      IF (Y(J).GT.0.0) GO TO 730
  730 T(J+1)=T(J)+0.1
      GO TO 101
  731 KK=KK+1
      GO TO 810
   16 T(J+1)=T(J-2)+0.01
      KK=KK+1
      GO TO 101
   17 IF (T(J).GT.1165.4) GO TO 325
      IF (Y(J).LE.0.0) GO TO 201
      IF (Y(J).GT.0.0) GO TO 732
  732 T(J+1)=T(J)+0.01
      GO TO 101
  705 T(J+1)=T(J)+10.0
  101 CONTINUE
C
  201 IF (NTRA.EQ.0) GO TO 86
      IF (NTRA.EQ.1) GO TO 88
C
   86 SPFT=VF*(1.0-X2)+VG*X2
      DFT=1.0/SPFT
      W(LL)=T(J)
      KR=0
      CALL WASP(2,0,W(LL),PFT(LL),DFT,H,KR)
      GO TO 89
C
   88 SPTZ=VF*(1.0-X2)+VG*X2
      DTZ=1.0/SPTZ
      WZ(JZ)=T(J)
      KR=0
      CALL WASP(2,0,WZ(JZ),PTZ(JZ),DTZ,H,KR)
C
   89 IF (NTRA.EQ.0) GO TO 742
      IF (NTRA.EQ.1) GO TO 755
C
C        CHECK FOR PHASE CHANGE
C
  742 IF (KR.EQ.1) GO TO 320
      IF (KR.EQ.2) GO TO 320
      IF (KR.EQ.3) GO TO 325
C
  325 WRITE(6,330)
  330 FORMAT(/,35X,'*** IN THE SUPERHEATED STEAM REGION ***')
C
C        PHASE CHANGE - TWO PHASE TO SUPERHEATED STEAM
C
      L=LL
      NTRA=1
```

```
C
C        LOCATE THE TRANSITION POINT
C
      IF (KCOND.EQ.1) GO TO 820
      IF (KCOND.EQ.2) GO TO 822
C
  820 WWTP(1)=WPFT(IJK,LL-1)
      WWTP(2)=WPFT(IJK,LL-1)
      WWTE(1)=WEFT(LL-1)
      WWTE(2)=WEFT(LL-1)
      WWTL(1)=WLFT(LL-1)
      WWTL(2)=WLFT(LL-1)
      QQTS(1)=QSFT(LL-1)
      QQTS(2)=QSFT(LL-1)
      GO TO 825
C
  822 WWTP(1)=WWPP(LL-1)
      WWTP(2)=WWPP(LL-1)
      WWTE(1)=WWEE(LL-1)
      WWTE(2)=WWEE(LL-1)
      WWTL(1)=WWLL(LL-1)
      WWTL(2)=WWLL(LL-1)
      QQTS(1)=QQSS(LL-1)
      QQTS(2)=QQSS(LL-1)
C
  825 DO 750 JZ=2,200
      WWTC(JZ)=X(2)-WWTP(JZ)-WWTL(JZ)+WWTE(JZ)
      IF (WWTC(JZ).LT.0.0) GO TO 96
      GO TO 772
C
C        CHECK FOR PHASE CHANGE
C
  755 IF (KR.EQ.1) GO TO 83
      IF (KR.EQ.3) GO TO 84
C
C        ITERATE BY 0.001
C
   83 WWTP(JZ+1)=WWTP(JZ)*(1.0+0.001)
      WWTE(JZ+1)=WWTE(JZ)*(1.0+0.001)
      WWTL(JZ+1)=WWTL(JZ)*(1.0+0.001)
      QQTS(JZ+1)=QQTS(JZ)*(1.)+0.001)
  750 CONTINUE
C
C        CURRENT MASS @ TRANSITION POINT, WWTT
C
   84 WWTT=WWTC(JZ)
      TC=T(J)
      TI=T(J)
      KR=0
      CALL WASP(1,0,TI,PTZ(JZ),DZ,H,KR)
      VTZ=1.0/DZ
      ZZ=(10.73*TI)/(VTZ*18.0)
      IF (KCOND.EQ.1) GO TO 460
      IF (KCOND.EQ.2) GO TO 462
  460 YYY=(WPFT(IJK,LL)-WWTP(JZ))/(WPFT(IJK,LL)-WPFT(IJK,LL-1))
      GO TO 465
  462 YYY=(WWPP(LL)-WWTP(JZ))/(WWPP(LL)-WWPP(LL-1))
  465 GO TO 41
C
```

*** SATURATED LIQUID-STEAM RESERVOIR ***

FINAL VALUES

LEAST SQUARES = 0

INITIAL TEMPERATURE = 952.518799

INITIAL MASS = 1.875924990 12

INITIAL STEAM QUALITY = 0.078475

RESERVOIR PROPERTIES

POROSITY = 0.20000

ROCK DENSITY = 190.00000

INFLUX TEMPERATURE = 960.00000

	KR	ACTUAL PRESSURE	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	618.0000	615.9988	948.82000	1.0180000 12	1.0000000 00	1.0000000 00	1.0000000 00	0.19912
2	1	638.0000	638.6403	947.52000	1.1600000 12	2.0000000 00	2.0000000 00	2.0000000 00	0.24101
3	1	597.0000	599.0072	945.80000	1.2910000 12	3.0000000 00	3.0000000 00	3.0000000 00	0.29603
4	1	587.0000	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 1.000000000 08

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	587.0208	943.63000	1.4031000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.36463
3	1	587.0208	943.63000	1.4032000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.36472
4	1	586.9660	943.62000	1.4033000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.36476

5	1	586.9660	943.62000	1.4034000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.36495
6	1	586.9660	943.62000	1.4035000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.36493
7	1	586.9660	943.62000	1.4036000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.36501
8	1	586.9112	943.61000	1.4037000 12	1.1000000 01	1.1000000 01	1.1000000 01	0.36506
9	1	586.9112	943.61000	1.4038000 12	1.2000000 01	1.2000000 01	1.2000000 01	0.36514
10	1	586.9112	943.61000	1.4039000 12	1.3000000 01	1.3000000 01	1.3000000 01	0.36522
11	1	586.9112	943.61000	1.4040000 12	1.4000000 01	1.4000000 01	1.4000000 01	0.36531
12	1	586.8564	943.60000	1.4041000 12	1.5000000 01	1.5000000 01	1.5000000 01	0.36535
13	1	586.8564	943.60000	1.4042000 12	1.6000000 01	1.6000000 01	1.6000000 01	0.36544
14	1	586.8564	943.60000	1.4043000 12	1.7000000 01	1.7000000 01	1.7000000 01	0.36552
15	1	586.8564	943.60000	1.4044000 12	1.8000000 01	1.8000000 01	1.8000000 01	0.36560
16	1	586.8564	943.60000	1.4045000 12	1.9000000 01	1.9000000 01	1.9000000 01	0.36569
17	1	586.8016	943.59000	1.4046000 12	2.0000000 01	2.0000000 01	2.0000000 01	0.36573
18	1	586.8016	943.59000	1.4047000 12	2.1000000 01	2.1000000 01	2.1000000 01	0.36582
19	1	586.8016	943.59000	1.4048000 12	2.2000000 01	2.2000000 01	2.2000000 01	0.36590
20	1	586.8016	943.59000	1.4049000 12	2.3000000 01	2.3000000 01	2.3000000 01	0.36598
21	1	586.7468	943.58000	1.4050000 12	2.4000000 01	2.4000000 01	2.4000000 01	0.36603
22	1	586.7468	943.58000	1.4051000 12	2.5000000 01	2.5000000 01	2.5000000 01	0.36611
23	1	586.7468	943.58000	1.4052000 12	2.6000000 01	2.6000000 01	2.6000000 01	0.36620
24	1	586.7468	943.58000	1.4053000 12	2.7000000 01	2.7000000 01	2.7000000 01	0.36628
25	1	586.6920	943.57000	1.4054000 12	2.8000000 01	2.8000000 01	2.8000000 01	0.36633
26	1	586.6920	943.57000	1.4055000 12	2.9000000 01	2.9000000 01	2.9000000 01	0.36641
27	1	586.6920	943.57000	1.4056000 12	3.0000000 01	3.0000000 01	3.0000000 01	0.36649
28	1	586.6920	943.57000	1.4057000 12	3.1000000 01	3.1000000 01	3.1000000 01	0.36658
29	1	586.6372	943.56000	1.4058000 12	3.2000000 01	3.2000000 01	3.2000000 01	0.36662
30	1	586.6372	943.56000	1.4059000 12	3.3000000 01	3.3000000 01	3.3000000 01	0.36671

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 1.000000000 09

KR		CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455

2	1	586.9112	943.61000	1.4040000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.36531
3	1	586.7468	943.58000	1.4050000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.36603
4	1	586.6372	943.56000	1.4060000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.36679
5	1	586.5276	943.54000	1.4070000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.36756
6	1	586.3633	943.51000	1.4080000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.36829
7	1	586.2536	943.49000	1.4090000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.36906
8	1	586.0896	943.46000	1.4100000 12	1.1000000 01	1.1000000 01	1.1000000 01	0.36980
9	1	585.9801	943.44000	1.4110000 12	1.2000000 01	1.2000000 01	1.2000000 01	0.37057
10	1	585.8706	943.42000	1.4120000 12	1.3000000 01	1.3000000 01	1.3000000 01	0.37136
11	1	585.7064	943.39000	1.4130000 12	1.4000000 01	1.4000000 01	1.4000000 01	0.37210
12	1	585.5970	943.37000	1.4140000 12	1.5000000 01	1.5000000 01	1.5000000 01	0.37289
13	1	585.4329	943.34000	1.4150000 12	1.6000000 01	1.6000000 01	1.6000000 01	0.37365
14	1	585.3235	943.32000	1.4160000 12	1.7000000 01	1.7000000 01	1.7000000 01	0.37444
15	1	585.1595	943.29000	1.4170000 12	1.8000000 01	1.8000000 01	1.8000000 01	0.37520
16	1	585.0501	943.27000	1.4180000 12	1.9000000 01	1.9000000 01	1.9000000 01	0.37600
17	1	584.8861	943.24000	1.4190000 12	2.0000000 01	2.0000000 01	2.0000000 01	0.37677
18	1	584.7768	943.22000	1.4200000 12	2.1000000 01	2.1000000 01	2.1000000 01	0.37758
19	1	584.6129	943.19000	1.4210000 12	2.2000000 01	2.2000000 01	2.2000000 01	0.37835
20	1	584.5036	943.17000	1.4220000 12	2.3000000 01	2.3000000 01	2.3000000 01	0.37917
21	1	584.3397	943.14000	1.4230000 12	2.4000000 01	2.4000000 01	2.4000000 01	0.37995
22	1	584.2305	943.12000	1.4240000 12	2.5000000 01	2.5000000 01	2.5000000 01	0.38077
23	1	584.0667	943.09000	1.4250000 12	2.6000000 01	2.6000000 01	2.6000000 01	0.38156
24	1	583.9029	943.06000	1.4260000 12	2.7000000 01	2.7000000 01	2.7000000 01	0.38235
25	1	583.7937	943.04000	1.4270000 12	2.8000000 01	2.8000000 01	2.8000000 01	0.38319
26	1	583.6300	943.01000	1.4280000 12	2.9000000 01	2.9000000 01	2.9000000 01	0.38399
27	1	583.5209	942.99000	1.4290000 12	3.0000000 01	3.0000000 01	3.0000000 01	0.38483
28	1	583.3572	942.96000	1.4300000 12	3.1000000 01	3.1000000 01	3.1000000 01	0.38563
29	1	583.1936	942.93000	1.4310000 12	3.2000000 01	3.2000000 01	3.2000000 01	0.38644
30	1	583.0845	942.91000	1.4320000 12	3.3000000 01	3.3000000 01	3.3000000 01	0.38729

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 1.000000000 10

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	585.7064	943.39000	1.4130000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.37210
3	1	584.3397	943.14000	1.4230000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.37965
4	1	582.9205	942.88000	1.4330000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.38811
5	1	581.4504	942.61000	1.4430000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.39661
6	1	579.9283	942.33000	1.4530000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.40547
7	1	578.3010	942.03000	1.4630000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.41467
8	1	576.6771	941.73000	1.4730000 12	1.1000000 01	1.1000000 01	1.1000000 01	0.42433
9	1	574.9488	941.41000	1.4830000 12	1.2000000 01	1.2000000 01	1.2000000 01	0.43440
10	1	573.1168	941.07000	1.4930000 12	1.3000000 01	1.3000000 01	1.3000000 01	0.44490
11	1	571.2356	940.72000	1.5030000 12	1.4000000 01	1.4000000 01	1.4000000 01	0.45592
12	1	569.2520	940.35000	1.5130000 12	1.5000000 01	1.5000000 01	1.5000000 01	0.46745
13	1	567.1670	939.96000	1.5230000 12	1.6000000 01	1.6000000 01	1.6000000 01	0.47954
14	1	564.9813	939.55000	1.5330000 12	1.7000000 01	1.7000000 01	1.7000000 01	0.49223
15	1	562.6959	939.12000	1.5430000 12	1.8000000 01	1.8000000 01	1.8000000 01	0.50559
16	1	560.2589	938.66000	1.5530000 12	1.9000000 01	1.9000000 01	1.9000000 01	0.51963
17	1	557.7246	938.18000	1.5630000 12	2.0000000 01	2.0000000 01	2.0000000 01	0.53445
18	1	555.0414	937.67000	1.5730000 12	2.1000000 01	2.1000000 01	2.1000000 01	0.55009
19	1	552.2636	937.14000	1.5830000 12	2.2000000 01	2.2000000 01	2.2000000 01	0.56669
20	1	549.2358	936.56000	1.5930000 12	2.3000000 01	2.3000000 01	2.3000000 01	0.58418
21	1	546.1171	935.96000	1.6030000 12	2.4000000 01	2.4000000 01	2.4000000 01	0.60283
22	1	542.7537	935.31000	1.6130000 12	2.5000000 01	2.5000000 01	2.5000000 01	0.62260
23	1	539.2007	934.62000	1.6230000 12	2.6000000 01	2.6000000 01	2.6000000 01	0.64368
24	1	535.4101	933.88000	1.6330000 12	2.7000000 01	2.7000000 01	2.7000000 01	0.66618
25	1	531.3351	933.08000	1.6430000 12	2.8000000 01	2.8000000 01	2.8000000 01	0.69021
26	1	527.0315	932.23000	1.6530000 12	2.9000000 01	2.9000000 01	2.9000000 01	0.71606
27	1	522.3534	931.30000	1.6630000 12	3.0000000 01	3.0000000 01	3.0000000 01	0.74377
28	1	517.3588	930.30000	1.6730000 12	3.1000000 01	3.1000000 01	3.1000000 01	0.77370
29	1	512.0057	929.22000	1.6830000 12	3.2000000 01	3.2000000 01	3.2000000 01	0.80613
30	1	506.2056	928.04000	1.6930000 12	3.3000000 01	3.3000000 01	3.3000000 01	0.84132

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 1.250000000 10

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	585.3782	943.33000	1.4155000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.37404
3	1	583.6300	943.01000	1.4280000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.38399
4	1	581.8314	942.68000	1.4405000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.39446
5	1	579.9283	942.33000	1.4530000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.40547
6	1	577.9217	941.96000	1.4655000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.41706
7	1	575.8124	941.57000	1.4780000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.42930
8	1	573.5474	941.15000	1.4905000 12	1.1000000 01	1.1000000 01	1.1000000 01	0.44220
9	1	571.2356	940.72000	1.5030000 12	1.2000000 01	1.2000000 01	1.2000000 01	0.45592
10	1	568.7169	940.25000	1.5155000 12	1.3000000 01	1.3000000 01	1.3000000 01	0.47040
11	1	566.0467	939.75000	1.5280000 12	1.4000000 01	1.4000000 01	1.4000000 01	0.48577
12	1	563.2799	939.23000	1.5405000 12	1.5000000 01	1.5000000 01	1.5000000 01	0.50219
13	1	560.2589	938.66000	1.5530000 12	1.6000000 01	1.6000000 01	1.6000000 01	0.51963
14	1	557.0923	938.06000	1.5655000 12	1.7000000 01	1.7000000 01	1.7000000 01	0.53831
15	1	553.6774	937.41000	1.5780000 12	1.8000000 01	1.8000000 01	1.8000000 01	0.55828
16	1	550.0176	936.71000	1.5905000 12	1.9000000 01	1.9000000 01	1.9000000 01	0.57972
17	1	546.1171	935.96000	1.6030000 12	2.0000000 01	2.0000000 01	2.0000000 01	0.60283
18	1	541.8767	935.14000	1.6155000 12	2.1000000 01	2.1000000 01	2.1000000 01	0.62773
19	1	537.3029	934.25000	1.6280000 12	2.2000000 01	2.2000000 01	2.2000000 01	0.65470
20	1	532.3516	933.28000	1.6405000 12	2.3000000 01	2.3000000 01	2.3000000 01	0.68401
21	1	527.0315	932.23000	1.6530000 12	2.4000000 01	2.4000000 01	2.4000000 01	0.71606
22	1	521.1514	931.06000	1.6655000 12	2.5000000 01	2.5000000 01	2.5000000 01	0.75106
23	1	514.7265	929.77000	1.6780000 12	2.6000000 01	2.6000000 01	2.6000000 01	0.78958
24	1	507.6754	928.34000	1.6905000 12	2.7000000 01	2.7000000 01	2.7000000 01	0.83220
25	1	499.8741	926.74000	1.7030000 12	2.8000000 01	2.8000000 01	2.8000000 01	0.87959
26	1	491.2077	924.94000	1.7155000 12	2.9000000 01	2.9000000 01	2.9000000 01	0.93263
27	1	481.5255	922.90000	1.7280000 12	3.0000000 01	3.0000000 01	3.0000000 01	0.99244

*** IN THE SUPERHEATED STEAM REGION ***

28	3	450.6068	922.59000	1.0772950 10 1.7405000 12	8.6183590-01 3.1000300 01	8.6183590-01 3.1000000 01	8.6183590-01 3.1000000 01	1.00000
29	3	415.5536	922.59000	2.3272950 10 1.7530000 12	1.8618360 00 3.2000000 01	1.8618360 00 3.2000000 01	1.8618360 00 3.2000000 01	1.00000
30	3	379.1381	922.59000	3.5772950 10 1.7655000 12	2.8618360 00 3.3000000 01	2.8618360 00 3.3000000 01	2.8618360 00 3.3000000 01	1.00000

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 2.0000000000 10

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.9208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	583.6300	943.01000	1.4280000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.38359
3	1	579.9283	942.33000	1.4530000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.40547
4	1	575.8124	941.57000	1.4780000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.42930
5	1	571.2356	940.72000	1.5030000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.45592
6	1	566.0467	939.75000	1.5280000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.48577
7	1	560.2599	938.66000	1.5530000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.51953
8	1	553.6774	937.41000	1.5780000 12	1.1000000 01	1.1000000 01	1.1000000 01	0.55828
9	1	546.1171	935.96000	1.6030000 12	1.2000000 01	1.2000000 01	1.2000000 01	0.60283
10	1	537.3029	934.25000	1.6280000 12	1.3000000 01	1.3000000 01	1.3000000 01	0.65470
11	1	527.0315	932.23000	1.6530000 12	1.4000000 01	1.4000000 01	1.4000000 01	0.71606
12	1	514.7265	929.77000	1.6780000 12	1.5000000 01	1.5000000 01	1.5000000 01	0.78958
13	1	499.8741	926.74000	1.7030000 12	1.6000000 01	1.6000000 01	1.6000000 01	0.87959
14	1	481.5255	922.90000	1.7280000 12	1.7000000 01	1.7000000 01	1.7000000 01	0.99244

*** IN THE SUPERHEATED STEAM REGION ***

15	3	415.5536	922.59000	2.3272950 10 1.7530000 12	9.3091800-01 1.8000000 01	9.3091800-01 1.8000000 01	9.3091800-01 1.8000000 01	1.00000
16	3	341.3681	922.59000	4.8272950 10 1.7780000 12	1.9309180 00 1.9000000 01	1.9309180 00 1.9000000 01	1.9309180 00 1.9000000 01	1.00000
17	3	261.8038	922.59000	7.3272950 10 1.8030000 12	2.9309180 00 2.0000000 01	2.9309180 00 2.0000000 01	2.9309180 00 2.0000000 01	1.00000
18	3	176.9553	922.59000	9.8272950 10 1.8280000 12	3.9309180 00 2.1000000 01	3.9309180 00 2.1000000 01	3.9309180 00 2.1000000 01	1.00000

19	3	86.9446	922.59000	1.2327290 11 1.8530000 12	4.9309180 00 2.2000000 01	4.9309180 00 2.2000000 01	4.9309180 00 2.2000000 01	1.00000

*** CURRENT MASS IS LESS THAN ZERO ***

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 5.000000000 10

	KP	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	579.9283	942.33000	1.4530000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.40547
3	1	571.2356	940.72000	1.5030000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.45592
4	1	560.2589	938.66000	1.5530000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.51963
5	1	546.1171	935.96000	1.6030000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.60283
6	1	527.0315	932.23000	1.6530000 12	9.0000000 00	9.0000000 00	9.0000000 00	0.71606
7	1	499.8741	926.74000	1.7030000 12	1.0000000 01	1.0000000 01	1.0000000 01	0.87959

*** IN THE SUPERHEATED STEAM REGION ***

8	3	415.4653	922.46000	2.2561880 10 1.7530000 12	4.5123750-01 1.1000000 01	4.5123750-01 1.1000000 01	4.5123750-01 1.1000000 01	1.00000
9	3	261.7571	922.46000	7.2561880 10 1.6030000 12	1.4512380 00 1.2000000 01	1.4512380 00 1.2000000 01	1.4512380 00 1.2000000 01	1.00000
10	3	86.9315	922.46000	1.2256190 11 1.8530000 12	2.4512380 00 1.3000000 01	2.4512380 00 1.3000000 01	2.4512380 00 1.3000000 01	1.00000

*** CURRENT MASS IS LESS THAN ZERO ***

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 7.500000000 10

	KP	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	575.8124	941.57000	1.4780000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.42930
3	1	560.2589	938.66000	1.5530000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.51963

4	1	537.3029	934.25000	1.6280000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.65470
5	1	499.8741	926.74000	1.7030000 12	8.0000000 00	8.0000000 00	8.0000000 00	0.87959

*** IN THE SUPERHEATED STEAM REGION ***

6	3	341.3017	922.46000	4.7561880 10 1.7780000 12	6.3415840-01 9.0000000 00	6.3415840-01 9.0000000 00	6.3415340-01 9.0000000 00	1.00000
7	3	86.6315	922.46000	1.2256190 11 1.8530000 12	1.6341580 00 1.0000000 01	1.6341580 00 1.0000000 01	1.6341580 00 1.0000000 01	1.00000

*** CURRENT MASS IS LESS THAN ZERO ***

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 1.000000000 11

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	571.2356	940.72000	1.5030000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.45592
3	1	546.1171	935.96000	1.6030000 12	6.0000000 00	6.0000000 00	6.0000000 00	0.60283
4	1	499.8741	926.74000	1.7030000 12	7.0000000 00	7.0000000 00	7.0000000 00	0.87959

*** IN THE SUPERHEATED STEAM REGION ***

5	3	261.7571	922.46000	7.2561880 10 1.8030000 12	7.2561880-01 8.0000000 00	7.2561880-01 8.0000000 00	7.2561880-01 8.0000000 00	1.00000

*** CURRENT MASS IS LESS THAN ZERO ***

*** FUTURE PERFORMANCE PREDICTION OF A GEOTHERMAL RESERVOIR ***

MASS PRODUCTION RATE,LBS/UNIT TIME = 2.500000000 11

	KR	CALCULATED PRESSURE	CURRENT TEMPERATURE	MASS PRODUCED	MASS INFLUX	MASS LOST	HEAT INFLUX	STEAM QUALITY
1	1	587.0208	943.63000	1.4030000 12	4.0000000 00	4.0000000 00	4.0000000 00	0.36455
2	1	527.0315	932.23000	1.6530000 12	5.0000000 00	5.0000000 00	5.0000000 00	0.71606

*** CURRENT MASS IS LESS THAN ZERO ***

APPENDIX F

COMPUTER SUBPROGRAM WASP

USER'S GUIDE

WASP User's Guide

As mentioned earlier, WASP is a subroutine which calculates the thermodynamic and transport properties of water and steam. The input-output control parameters must be correctly specified to obtain the desired parameter values. These control parameters will be discussed in the following paragraphs.

Parameter KU is an input control which identifies the unit system for the input and output (Table 26). The option KU=1 is the internal program unit system. KU=3 was the value used in the HGP model study.

The controls KR, KS, and KP tell WASP which variables are to be used as input and which properties are requested as output. KS and KR are controls that determine which of the variables T (temperature), P (pressure), D (density), H (enthalpy), or S (entropy) or combinations thereof are needed as thermodynamic input. Table 27 illustrates the different combinations available. KP is an input control, which specifies the other properties sought as output. It is the sum of the individual KP options (Table 28) which is used.

KR as an output variable gives the correct region number for the variable in a specific call to WASP (Figure 41). As an input parameter, KR must be reset before each call to WASP. The input options are:

KR = 0 WASP determines a value for KR

= 1 saturation conditions are specified

The output for KR (=KCOND) will be:

KR = 1 saturated liquid-steam region

= 2 compressed liquid region

= 3 superheated steam region

Table 26. Units Specification [26]

Physical quantity	Units specification		
	KU=1	KU=2	* KU=3
Temperature	°K	°K	°R
Density	g/cm^3	g/cm^3	lb_m/ft^3
Pressure	MN/m^2	atmospheres	psia
Enthalpy	joule/g	joule/g	Btu/lb_m
Entropy, Specfic Heat	joule/g-°K	joule/g-°K	Btu/lb_m-°R
Sonic Velocity	cm/sec	cm/sec	ft/sec
Dynamic Viscosity	g/cm-sec	g/cm-sec	lb_m/ft-sec
Thermal Conductivity	joule/cm-sec-°K	joule/cm-sec-°K	Btu/ft-sec-°R
Surface Tension	dyne/cm	dyne/cm	lb_f/ft

* value used in HGP model

Table 27. Input and Output for all KS-KR Combinations [26]

Thermodynamic Region Specification	State Relation Specification, KS				
KR	1	2	3	4	5
	INPUT				
0	T and P	T and D	P and D	P and H	P and S
1	T or P[a]	T	P	P	P
	OUTPUT				
1	T or P[a], DL and DV	P	T	T, DL, DV	T, DL, DV
2	D	P	T	D and T	D and T
3	D	P	T	D and T	D and T

[a]If T is the desired input, set P=0.0 prior to the call and vice versa. WASP will return the correct saturation value for the 0.0 input. If both T and P have an input value ≠0.0, WASP uses T but will not alter P input.

DL = saturated liquid density
DV = saturated vapor density

Table 28. Output Locations for the Specific KR and KP Combinations [26]

Value added to KP input	Output for KR=2 or 3	Output for KR=1		Name of calculated property
		Liquid	Vapor	
0	-	-	-	None requested
1	H	HL	HV	Enthalpy
2	S	SL	SV	Entropy
4	CP	CPL	CPV	Specific heat at constant pressure
	CV	CVL	CVV	Specific heat at constant volume
	GAMMA	GAMMAL	GAMMAV	Specific heat ratio
	C	CL	CVP	Sonic velocity
8	MU	MUL	MUV	Viscosity
16	K	KL	KV	Thermal conductivity
32	SIGMA	SIGMA	-	Surface tension of the liquid as a function of temperature
	ALC	ALC	-	Laplace constant as a function of temperature

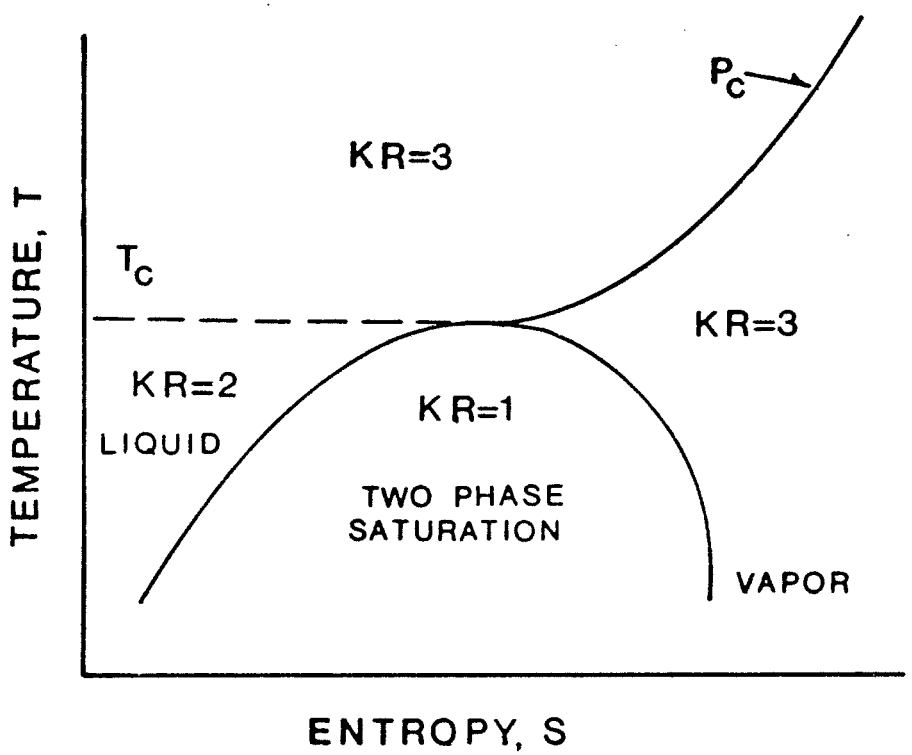


Figure 41. KR Output for WASP [26]

APPENDIX G

GENERAL EQUATIONS FOR

THERMODYNAMIC PROPERTIES OF WATER

$$HF = 245.418777 + 27.3585358((T°R-460)/100) + 5.24177074((T°R-460)/100)^2 + 0.34823012((T°R-460)/100)^3 - 344.718262/((T°R-460)/100) \quad (36)$$

$$HG = 1021.10571 + 16.3022919((T°R-460)/100) + 13.8019953((T°R-460)/100)^2 - 2.18339539((T°R-460)/100)^3 + 134.681641/((T°R-460)/100) \quad (37)$$

$$VF = 0.01792239 + 0.00215744((T°R-460)/100) - 0.00076399((T°R-460)/100)^2 + 0.0000997((T°R-460)/100)^3 - 0.00839130/((T°R-460)/100) \quad (38)$$

$$VG = DEXP(0.90465665 - 0.49597612((T°R-460)/100) - 0.01500756((T°R-460)/100)^2 + 7.75882149/((T°R-460)/100)) \quad (39)$$

BIBLIOGRAPHY

[1] Takahashi, P.K. "Alternate Energy Futures: New Technologies for Paradise." (Coordinator), ECOPUSH Conference Proceedings, May 1974.

[2] Takahashi, P.K. and Bill H. Chen. "Geothermal Reservoir Engineering." Geothermal Energy, Vol. 3, No. 10, (October 1975), pp. 7-23.

[3] Cady, G.V., H.L. Bilhartz Jr., and Henry J. Ramey Jr. "Model Studies of Geothermal Steam Production." Water 1972, A.I.Ch.E. Symposium Series, 1973.

[4] Whiting, R.L. and H.J.Ramey Jr. "Application of Material and Energy Balances to Geothermal Steam Production." J. Pet. Tech., Vol. 246, (July 1969), pp. 893-900.

[5] White, D.E., L.J.P. Muffler, and A.H. Truesdell. "Vapor-Dominated Hydrothermal Systems Compared with Hot-Water Systems." Econ. Geology, Vol. 66, No. 1, (January-February 1971), pp. 75-97.

[6] Facca, Giancarlo. "The Structure and Behavior of Geothermal Fields." Geothermal Energy (Earth Science, 12), U.N.E.S.C.O., 1973, pp. 61-69.

[7] Toronyi, R.M. Two-Phase, Two-Dimensional, Simulation of a Geothermal Reservoir and Well Bore System. Unpublished doctoral dissertation. Pennsylvannia State University, 1974.

[8] Combarnous, M.A. and S.A. Bories. "Hydrothermal Convection in Saturated Porous Media." Advances in Hydroscience. Academic Press, San Francisco, Vol. 10. 1975, pp. 231-308.

[9] Dench, N.D. "Well Measurements." Geothermal Energy (Earth Science, 12), U.N.E.S.C.O., 1973, pp. 85-96.

[10] Witherspoon, P.A., S.P. Neuman, M.L. Sorey, and M.J. Lippmann. "Modeling Geothermal Systems." Paper Presented at the International Meeting on Geological Phenomena and Its Applications, Rome, Italy, March 3-5, 1975.

[11] Brigram, William E. and Bruce W. Morrow. "P/Z Behavior for Geothermal Steam Reservoirs." Paper 4899, 44th Annual California Regional Meeting S.P.E.-A.I.M.E., San Francisco, April 4-5, 1974.

[12] Martin, J.C. "Analysis of Internal Steam Drive in Geothermal Reservoirs." Paper 5382, 45th Annual California Regional Meeting S.P.E.-A.I.M.E., Ventura, California, April 2-4, 1975.

[13] Ramey, H.J.,Jr., and et.al. "Thermodynamic and Hydrothermic Properties of Hydrothermal Systems." Paper Presented at the United States-Japan Seminar on Utilization of Volcano Energy, Hilo, Hawaii, February 1974.

[14] Lee, W.K. ed. Terrestrial Heat Flow. A.G.U. Monograph. No. 8, 1966.

[15] Matthews, C.S. and D.G. Russell. Pressure Buildup and Flow Tests in Wells. S.P.E. Monograph, Vol. 1, Dallas, 1967.

[16] Mashima, Ken I. An Assessment of Techniques for Testing Geothermal Wells. Unpublished master thesis. University of Hawaii, 1975.

[17] Matthews, C.S., F. Brons, and P. Hazebroek. "A Method for Determination of Average Pressure in a Bounded Reservoir." Transactions of the A.I.M.E., Vol. 201, 1954, pp. 182-191.

[18] Whiting, R.L. "Drilling and Production Techniques in Geothermal Reservoirs." Paper 5169, Paper Presented at the Deep Drilling and Production Symposium of the Society of Petroleum Engineerings, A.I.M.E., Amarillo, Texas, September 8-10, 1974.

[19] Takahashi, P.K., Bill H. Chen, Ken I. Mashima, and Arthur S. Seki. "State-of-the-Art of Geothermal Reservoir Engineering." Jour. of the Power Division, A.S.C.E., Vol. 101, No. PO1, (July 1975), pp. 111-126.

[20] Chou, J.C.S. "Thermal Properties of Sea Water." Technical Report No. 49, Water Resources Research Center, University of Hawaii, 1971.

[21] MacDonald, Gordon A. Personal communication to author.

[22] Chen, Bill H. Report on Geothermal Reservoir and Well Test Analysis. Hawaii Geothermal Project, University of Hawaii, 1974.

[23] Ramey, H.J.,Jr. "A Reservoir Engineering Study of the Geysers Geothermal Field." Submitted as Evidence, Reich and Reich: Petitioners versus Commissioners of Internal Revenue, 1969 Tax Court of the United States, 52TC, No. 74, 1970.

[24] Box, M.J. "A New Method of Constrained Optimization and a Comparison with Other Methods." Computer J., Vol. 8, 1965, pp. 42-52.

[25] Kuester, J.L. and J.H. Mize. Optimization Techniques with Fortran. McGraw-Hill, San Francisco, 1973.

[26] Hendricks, Robert L., Ildiko C. Peller, and Anne K. Baron. WASP-A Flexible Fortran IV Computer Code for Calculating Water and Steam Properties. N.A.S.A., Washington D.C., November 1973.

[27] Meyer, C.A. and et.al. Thermodynamic and Transport Properties of Steam. A.S.M.E., 1967.

[28] Schmidt, Ernst. Properties of Water and Steam in S.I.-Units. Springer-Verlag, New York, 1969.

[29] Keenan, Joseph H. and Frederick G. Keyes. Thermodynamic Properties of Steam. John Wiley and Sons Inc., New York, 1936.

[30] Mercer, James W. Personal communication to author. July 17, 1975.

[31] Bolton, R.S. Personal communication to author. February 23, 1976.

[32] Bolton R.S. "The Behavior of the Wairakei Geothermal Field During Exploitation." United Nations Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy, Vol. 2, Part 2, 1970.

[33] Whiting, R.L. "A Reservoir Engineering Study of the Wairakei Geothermal Steam Field." Report Submitted to Ministry of Works, Wellington, New Zealand, November 1, 1966.

[34] Ramey, H.J.,Jr. "Reservoir Engineering the Geothermal Steam Reservoir." [n.d.].